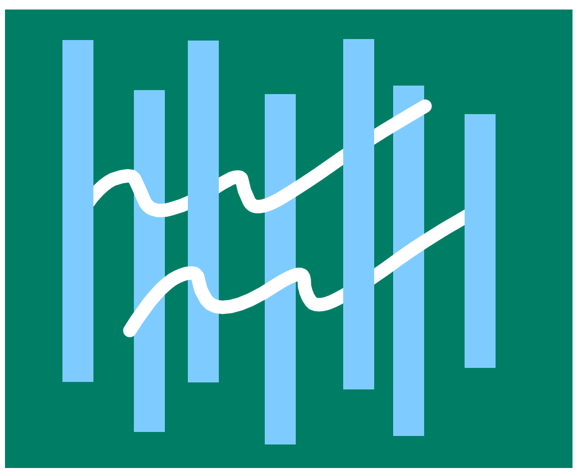
Highway Economic Requirements System-State Version

Technical Report



U.S. Department
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**Federal Highway
Administration**

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Chapter 1:

Introduction

The Highway Economic Requirements System-State Version (HERS-ST) is a software package that estimates the investment that would be required to achieve certain highway system performance levels. Alternatively, the software can be used to estimate the highway system performance that would result given various investment levels. HERS-ST considers capital improvement projects directed at correcting pavement and capacity deficiencies.

The HERS-ST model is a direct extension of the national-level HERS model. This model was developed by the Federal Highway Administration (FHWA) to examine the relationship between national investment levels and the condition and performance of the Nation's highways. FHWA uses the model to estimate future highway investment requirements under different scenarios. FHWA provides this information to the U.S. Congress in the biennial Status of the Nation's Highways, Bridges and Transit: Conditions and Performance Report to Congress.

The HERS-ST model includes not only the analytical engines which comprise the national model but also a graphical user interface (GUI) module. The GUI environment includes tools for organizing the HERS-ST workspace, performing the HERS analysis, and organizing and formatting program output.

1.1 HERS-ST Documentation

This Technical Report is part of a set of HERS-ST documentation. It consists of detailed technical discussions of the procedures, assumptions, algorithms, and inputs of the HERS-ST model, focusing on the analytical engines. The other HERS-ST documents are:

1.1.1 User's Guide

The *HERS-ST User's Guide* provides "hands-on" assistance to the analyst interested in using HERS-ST to evaluate alternative highway program and policy scenarios. It contains detailed information and procedures for using the many tools provided in the GUI.

1.1.2 Overview

The *HERS-ST Overview* offers a summary of the model's logic structure and the analytical, economic, and engineering procedures it utilizes.

1.1.3 Pilot Program Report

The *HERS-ST Pilot Program Report* summarizes the findings of the HERS-ST Pilot Program and discusses the steps taken to create the first version of HERS-ST intended for national distribution.

1.2 Technical Report

HERS-ST calculates the benefits resulting from potential highway improvements, quantifying three types of benefits to highway users (travel time, operating costs, and safety), benefits to highway agencies (reduced maintenance costs), and one "external" benefit (damage caused by vehicle emissions). The model also calculates the "residual value" of improvements with remaining service life at the end of the analysis period. The HERS-ST model uses benefit-cost analysis to evaluate potential improvements when selecting among candidate improvements for implementation. As part of its benefit calculations, HERS-ST captures the effect of improvements on traffic levels and the associated changes in pavement condition, pavement life, and user costs. Finally, the results of comparing alternatives are distilled into summary measures of benefits and costs for candidate improvements.

The remaining seven chapters of this Technical Report can be briefly summarized as follows:

Chapter 2: An Outline of the Model Structure

Describes the structure of the HERS-ST system and indicates generally how the model components are interrelated and the time and other dimensions over which the model operates.

Chapter 3: Inputs

Explains the different types of HERS-ST inputs, the processing performed by the HERS-ST PreProcessor, and several underlying HERS-ST assumptions.

Chapter 4: Design of Improvement Alternatives

Defines the different types of improvements that HERS-ST can implement to correct deficiencies identified for a section, and the impacts of these improvements on the highway and the user.

Chapter 5: Estimation of Impacts

Describes the way the HERS-ST models discrete processes, including: pavement wear, vehicle operating costs, crash costs, traffic forecasts, speed calculation, travel time costs, demand elasticity, agency costs, and external costs.

Chapter 6: Capital Cost of Improvements

Describes the initial costs of improvements used by HERS-ST, procedures used for estimating these costs, the model's methodology for adjusting costs from year to year, and the different state cost factors.

Chapter 7: Evaluating Improvements

Explaining the mechanics of how HERS-ST quantifies and discounts benefits, and evaluates projects using benefit-cost criteria.

Chapter 8: Model Output

Describes the output that is automatically generated by HERS-ST.

The Technical Report also includes six appendices providing additional background and detail about HERS-ST:

Appendix A: Default Deficiency Criteria Tables

Provides the suggested default values for the three different types of section deficiency criteria. Also explains the role of default design standards and user specified thresholds.

Appendix B: Induced Traffic and Induced Demand

Describes the concepts guiding several modifications that were made to the HERS-ST model to account for traffic effects.

Appendix C: Demand Elasticities for Highway Travel

Describes the procedure for establishing the values that represent the short-run generalized price elasticity of travel, and the estimation of the long-run share parameter.

Appendix D: Basic Theory of Highway Project Evaluation

Discusses the principles that have served as a guide in developing the economic portions of the HERS-ST model, and how the model embodies them.

Appendix E: Operating Cost Equations

Describes the disaggregated vehicle operating costs by vehicle type and component for both constant and variable speeds. Also explains the pavement condition adjustment factors for the constant speed operating costs.

Appendix F: Procedures for Estimating Air Pollution Costs

Discusses the effect that traffic volume, the mix of vehicle types, and average effective speed can have on air pollution, and how HERS-ST attempts to measure these effects.

Chapter 2:

An Outline of the Model Structure

A separate document, the HERS-ST *Overview* (September 2002), provides a conceptual description of the HERS "engine" (the analytic core of HERS-ST) for those interested in gaining an overall understanding of how the model works. The *Overview* is recommended to analysts who may have topics of particular concern (e.g., pavement wear) but want to know the context in which these topics relate to the rest of the model. The technical report in hand provides details of equations, parameters, and the sequence of processing.

While not a substitute for the *Overview*, this section provides enough description of the structure of the HERS system to indicate generally how the model components are interrelated and the time and other dimensions over which it operates.

2.1 The Process

The basic function of the HERS model is to conduct project evaluations using benefit-cost methods. Given a set of highway sections as input, HERS looks at each section in turn and decides whether an improvement is warranted and, if so, what type of improvement. These choices may be constrained by user-specified improvement types or by funding caps or performance requirements. After projects have been selected for a given time period or *funding* period, the model moves on to the next period.

HERS-ST can be run under several "scenarios." One of these selects all sections for improvement for which at least one alternative passes the benefit-cost threshold, and picks the improvement with the highest benefit-cost ratio (BCR) for that section. In this scenario, the evaluation of each project is independent of the evaluation of other sections. At a very general level, this process is illustrated in Figure 2-1.

The user may choose to constrain the scenario by limiting funds, or by imposing minimum performance requirements. HERS reacts to the constraints by making tradeoffs between one section and another among worthwhile (those that pass the minimum BCR threshold) improvements.

2.2 Project Evaluation

The scope of project evaluation in HERS encompasses three general steps, shown in Figure 2-2:

Design of Alternatives. HERS can look for deficiencies and suggest improvements to correct the deficiencies, or the user can, in various ways, mandate that a particular improvement be made.

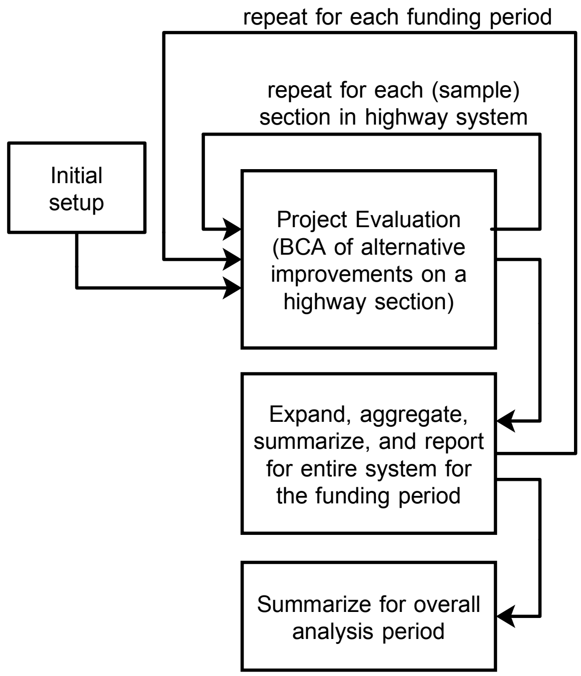

Figure 2-1. Overall HERS process

Impacts. The model estimates the conditions (traffic, pavement wear, accidents, emissions, etc.) that will occur under each alternative that is evaluated.

Evaluation. Differences in travel time, accidents, vehicle operating costs, and agency (maintenance) costs between the improvement and the base alternative are valued in present worth terms and compared to the cost of the improvement.

The structure of this technical report proceeds through these three steps.

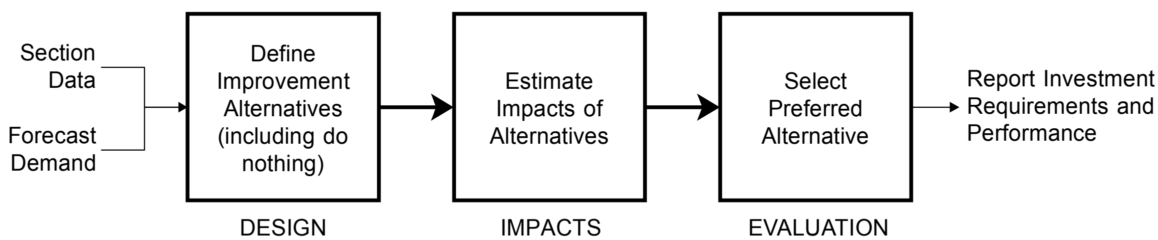

Figure 2-2. Major steps in project evaluation.

2.3 HERS Submodels

The HERS model has many routines (components or submodels) that perform specialized functions for the model as a whole. Some of these routines are simple calculations, using input data or the results from other routines, and some are complex procedures that may call other procedures. The procedures that are most important for estimating the impacts of project alternatives (base and improvement) on section conditions can be grouped into "models" (i.e., submodels of the HERS model) for explanatory purposes. These and their interrelationships are shown in Figure 2-3.

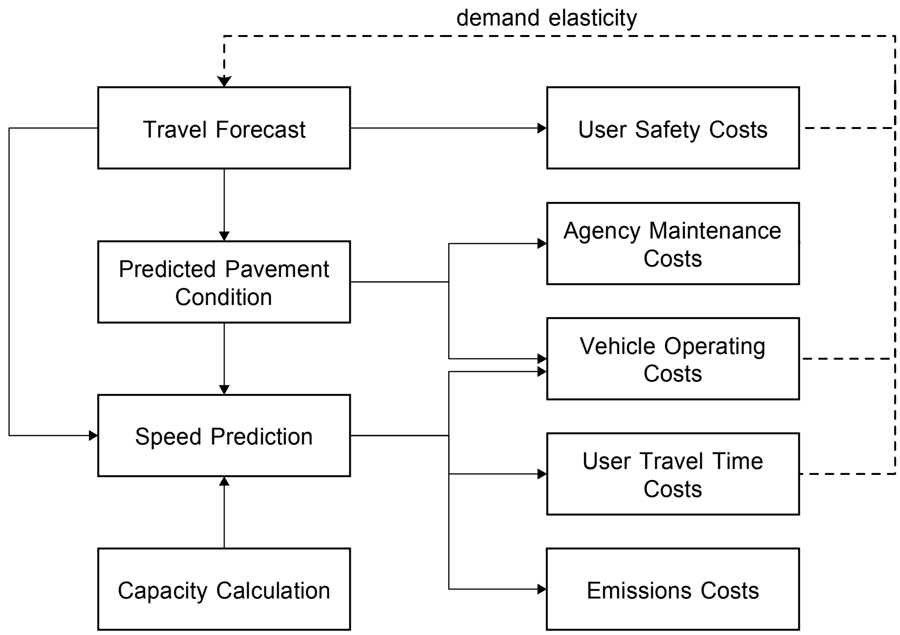

Figure 2-3. Prediction and calculation model linkages.

The dashed line represents the effect of costs to the user (the "price" of travel) on travel forecasts due to demand elasticity. The capacity calculation is invoked only after implementing an improvement.

For each funding period, for each sample section, for each of the logical sequences, the program performs the same set of predictions:

- predicts future traffic volume
- predicts future pavement conditions
- predicts current and future speeds
- predicts section capacity after improvement.

These predicted conditions are then used to calculate costs:

- costs to users of the highway system:
- operating costs
- travel time costs
- safety costs
- agency costs:
- capital improvement costs

- maintenance costs
- costs associated with vehicle emissions.

The information generated by the prediction and calculation models are used within the logic structure to evaluate and select improvements. The prediction and calculation models are discussed in detail in Chapter 5, “Estimation of Impacts.”

2.4 Price

HERS distinguishes three kinds of costs:

1. Resources consumed that constitute costs to society and also costs to users, in that users pay for them (e.g., travel time and vehicle operating costs).
2. Resources consumed that constitute costs to society but are not paid by users (or as a consequence of usage) and are therefore external costs or externalities (e.g., damage from pollution).
3. Transfers that are not costs to society but are regarded as costs by users (e.g., user taxes).

Costs of either of the first two kinds that are affected by an improvement are counted as benefits of the improvement. Transfers, the third kind of cost, amount to a gain by some persons and a loss by others, but no resources are consumed in the process (ignoring transaction costs). Tolls are paid by users and received by the owner of the road.

The distinctions are important not only for enumerating and quantifying benefits, but also for predicting the behavior of users, especially in response to a highway improvement. Users can be viewed as participants in a market, in which the volume of travel is affected by its price. In HERS, the price is the “generalized” cost of travel to the user, which includes travel time, other user costs, as well as user taxes and tolls.

An improvement that reduces the travel time between geographically dispersed locations is reducing the price of travel. If demand is not perfectly inelastic, more travel will ensue if the price is lower than if it is higher. The magnitude of this response is the travel demand elasticity, which may vary with the location, time of day, and whether the adjustment takes place in the short run or the long run, among many factors. Empirically, the elasticity of demand for highway travel is neither perfectly elastic (travel volume changes infinitely for even a miniscule change in price) nor perfectly inelastic (volume is the same no matter what the price). Elasticity concepts as applied in HERS allow for induced demand to occur in both the short and long run (See Appendix B, “Induced Traffic and Induced Demand” for an explanation of the elasticity concepts, Appendix C, “Demand Elasticities for Highway Travel” for ranges of empirical values, and section 5.6.2 “Applying Elasticity to Travel Volume Forecasts” on page 5-53 for the supply-demand algorithms).

2.5 Benefits and Costs

The scope of costs and benefits can be summarized in the form of a table, shown in Table 2-1. Changes in costs that constitute benefits are stated as cost reduction being a positive benefit, but the costs could also increase as a consequence of an improvement, resulting in negative benefits or disbenefits. Travel time might go down, for example, while accidents and emissions go up. Incremental consumer surplus is a representation of the user cost savings resulting from a change in the volume of travel as a result of non-zero elasticity. If the price goes down and travel increases, incremental consumer surplus is a positive contribution to benefits (see section 7.8.1 “Consumer Surplus” on page 7-8 for a description of the computations).

Table 2-1. Components of benefits and costs

	cost to user (price)	cost to society (benefit)
BENEFITS		
travel time cost savings	X	X
vehicle operating cost savings	X	X
accident cost savings	X	X
incremental consumer surplus	X	X
highway maintenance cost savings		X
residual value of facility		X
emissions reductions		X
COSTS		
initial improvement cost		X
TRANSFERS		
fuel excise taxes and tolls	X	

Any change in resource consumption that occurs as a consequence of an improvement is counted in the benefit category, except for the initial capital cost; this classification (cost or benefit) is important only for calculation of benefit-cost ratios. The goal is to maximize net benefits, and for this purpose it is only important to get the arithmetic sign correct (as well as, of course, the magnitude). Residual value might be regarded as a reduction in the capital cost of the improvement, but HERS treats it as a (discounted) benefit.

Hence items with an “X” in the cost-to-society column count as benefits, those with an “X” in the price column affect travel behavior through demand elasticity, and those items marked in both columns are both real social costs and also user costs. Those with an “X” only in the cost-to-society column are externalities, and those with an “X” only in the price column are transfers.

2.6 HERS Analytical Objectives

In any given run, HERS is designed to perform one of three types of analysis as specified in the user input field “Objective.” The user-specified objective may be in any of three possible forms:

1. Maximize the net present value of all benefits of highway improvements subject to specified constraints on funds available during the period;

2. Minimize the cost of improvements necessary to achieve a specified goal for the performance of the highway system at the end of the funding period; or

3. Implement all improvements with a benefit-cost ratio (BCR) greater than some specified threshold value.

The three forms are also referred to as Constrained Fund, Performance Constrained, and Minimum BCR, respectively.

When Objective is set to "1", HERS will solve for highway conditions and performance when improvements are constrained by available funds (referred to as a "constrained fund" run). When Objective is set to "2", HERS will solve for the funding levels required to bring the system to a specified level of performance (referred to as a "performance constrained" run). When Objective is set to "3", HERS will solve for both the required funding level and the resultant performance levels when improvements are constrained to return a minimum ratio of benefits relative to their cost (a "minimum benefit-cost ratio (BCR)" run). The model recognizes two special cases. The first is an "engineering needs" run (sometimes referred to as "full needs"), which is a minimum BCR run with the minimum BCR set to a very low negative number so that all sections with deficiencies are selected for improvement. The second is a "maintain current conditions" run in which the model first determines the level of system performance at the beginning of the run based on user-specified parameters (for example, current highway-user costs), and selects the least costly mix of improvements to maintain that level of performance. Each of the special cases can be selected via a dedicated input field. Finally, while a minimum BCR run where the minimum BCR is set to 1.0 is referred to as an "economic efficiency" run, this is not a different type of analysis, but a specific and often used Objective 3 scenario, and was used as the Maximum Economic Investment scenario in the 2002 *C&P Report*.

Objective 2 scenarios, such as the Maintain User Costs scenario of the 1997 *C&P Report*, can be specified as a goal for a single type of highway-user cost or highway agency cost per vehicle-mile (e.g., number of fatalities per vehicle-mile); or it can be specified as a dollar-valued composite of all net user and agency costs estimated by HERS (travel time costs, operating costs, fatality costs, injury costs, property damage, and maintenance costs). The dollar-valued composite can be obtained as a simple sum of the component costs or as the sum of two or more components with different weights. (The run specification file provides one set of weights used in balancing components of the incremental benefit-cost ratio, and another set for balancing components of the performance goal.) In the latter event, it is recommended (but not required) that the components of the IBCR be given weights that are consistent with the specified goal; e.g., the goal might be that the sum of user costs plus two times agency costs should not exceed $0.50 per vehicle-mile, in which case it is recommended that agency costs be weighted twice as heavily as user costs in the IBCR as well.

2.7 The HERS Process/Scenarios

The basic process is agreeably straightforward: forecast section condition; identify deficiencies and potential improvements; evaluate and select improvements; and implement improvements (or, for unimproved sections, implement the unimproved condition forecast for the end of the period). Output statistics are accumulated, and the process is repeated for each subsequent funding period. However, the model has two features (alternative improvement selection procedures, and mandatory correction of unacceptable conditions) which complicate the structure. Each feature offers a pair of alternatives, which, selected independently, define four distinct logical structures.

2.7.1 The Improvement Selection Procedures

The first feature is that the model supports two improvement selection procedures. Both procedures use benefit-cost analysis to choose between potential improvements, but one procedure chooses among improvement options for a single section at a time, while the other selects from all potential improvements to all sections in the system.

The "minimum BCR" alternative (Objective = 3) instructs the model to implement, for each deficient section, the most ambitious improvement which meets a minimum benefit-cost ratio. Under this option, all deficient sections with an "economically justifiable" candidate improvement are improved. An improvement is considered "economically justifiable" if its benefit-cost ratio is greater than or equal to the user-specified minimum. (For the "Economic Efficiency" scenario, the minimum BCR is set to 1.0.) Benefit-cost analysis is used first to determine if a section will be improved, and second to identify the most attractive of the potential improvements. (The improvement with the greatest BCR is considered more attractive.) The model is under no budget or performance constraints, but will implement the most attractive improvement for each qualifying section.

The "constrained" alternative (Objective = 1 or 2) effectively compels the model to rank all potential improvements, for all sections, in order of economic desirability (that is, ranked by BCR). The model then selects improvements in order of decreasing BCR until a specific constraint (available funds or system performance level) has been reached. While not all economically attractive improvements may be selected, those selected will all be more economically attractive than those not selected for implementation. When the constraint is available funds, the program selects the set of improvements which return the maximum benefit for the capital expenditure. When the program is constrained to attain a specific level of performance for the highway system, it selects the set of improvements which will achieve those goals at the lowest cost.

Figure 2-4 shows flow diagrams for these two selection procedures. In the minimum BCR version, the model selects a section's improvement immediately after evaluating the possible improvements. In the constrained run, the model "pre-selects" a section's most attractive improvement and places it on a list of potential improvements. After all sections have been evaluated, the model initiates a second selection procedure which selects improvements from the potential list (which is ordered by BCR) until the constraint, whether a budget limit or a performance goal, has been met.

The processes for identifying potential improvements are presented in Chapter 4, "Design of Improvement Alternatives."

2.7.2 Addressing Unacceptable Conditions

The second feature which can complicate the HERS selection process is the provision of a "safety-net" to force the model to improve unacceptably deficient sections with-

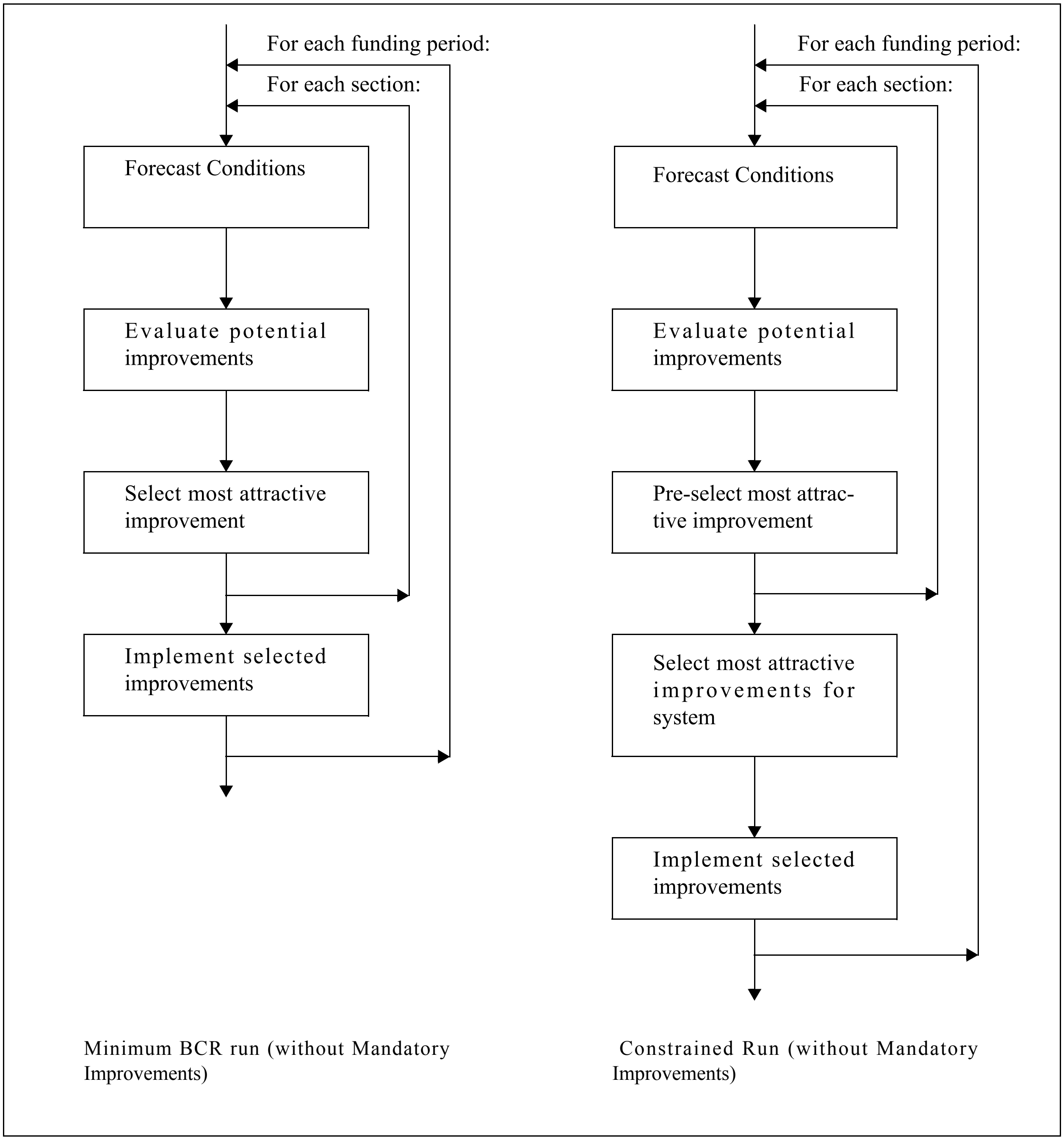

Figure 2-4. HERS Process Flow Without Mandatory Improvements

out regard for the economic desirability of the improvement. If this option is selected, HERS will make a special pass through all sections prior to the normal evaluation to identify low-cost improvements to correct unacceptable conditions. Improvements selected on this basis are referred to as “mandatory improvements.” For most purposes, such as preparation of data for the Conditions and Performance Report, the model is run without selecting this option, so no mandatory improvements are implemented.

The processing flow after the identification of mandatory improvements varies depending upon the analytical objective. The simplest case is illustrated in Figure 2-5 In this case, after identifying mandatory improvements for sections with unacceptable conditions, the program re-examines each section to identify economically attractive improvements. On a section for which a mandatory improvement has been identified, the model will implement either the mandatory improvement or an economically attractive improvement which also corrects all unacceptable conditions. On sections without mandatory improvements, the economically most attractive improvements will be implemented.

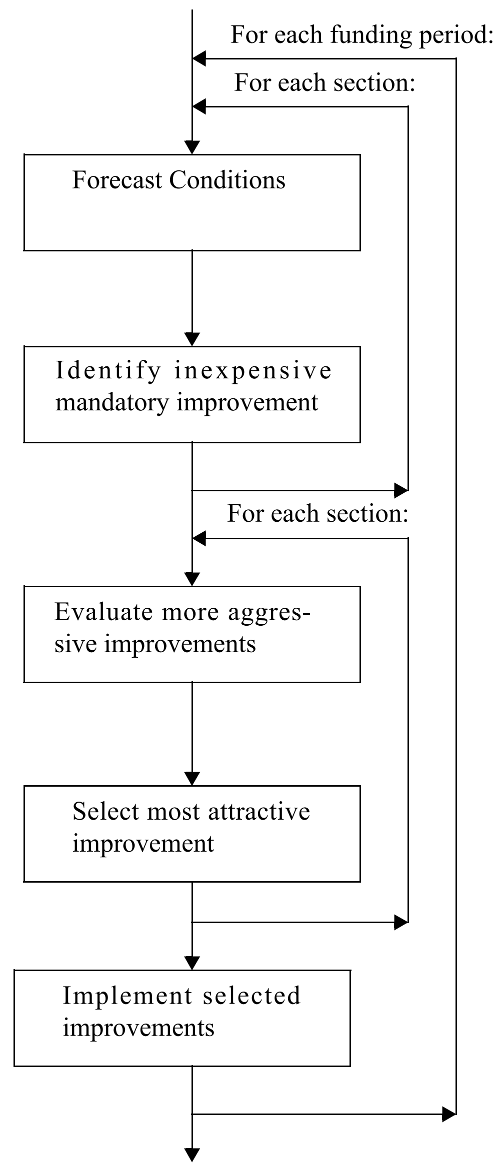

Figure 2-5. Minimum BCR Run with Mandatory Improvements

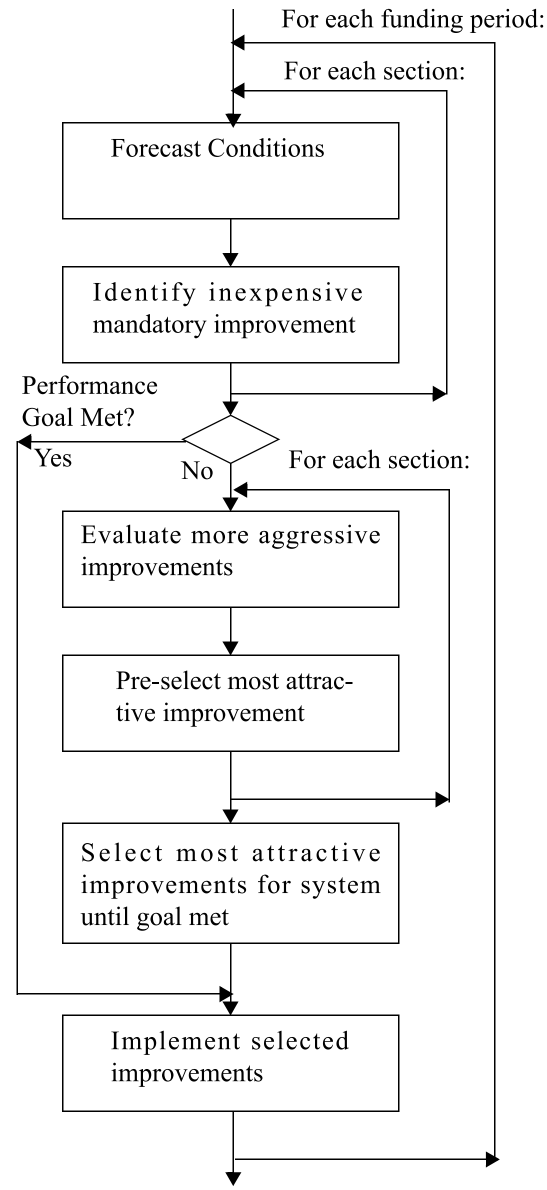

Figure 2-6. Performance Constrained Run With Mandatory Improvements

The processing flow for a performance constrained run with mandatory improvements is shown in Figure 2-6. In this type of run, the program forecasts the unimproved condition of the system at the end of the funding period, then implements improvements until the level of system performance reaches the specified goal. If implementing the mandatory improvements alone achieves the performance goal, no additional improvements are considered during this funding period. If the goal has yet to be achieved, the program loops through the sections again to identify economically attractive improvements, which are ordered by BCR and selected until the goal is attained.

Figure 2-7 shows the processing flow for a constrained fund run with mandatory improvements. For this scenario, the analyst specifies two funding levels: the total amount of funds to be expended per funding period, and the amount of the total funds which are to be used for more aggressive (that is, non-mandatory) improvements. For example, the analyst might specify that 100 million dollars be allocated for the first funding period, of which 70 million dollars is reserved for non-mandatory improvements. After identifying mandatory improvements for all sections, the program checks whether the cost of all mandatory improvements exceeds the 30 million dollars allocated for mandatory improvements.

If the mandatory improvements cost more than the funds allocated for them, the program selects from the mandatory improvements in order of their BCRs until it has expended all the available funds on the economically most attractive improvements. It then checks whether additional funds have been reserved for more aggressive (non-mandatory) improvements. If not, it implements the selected improvements and advances to the next funding period.

However, if funds were reserved for non-mandatory improvements, or if the mandatory improvements cost less than the funds allocated for them, the program loops through all the sections again to identify more aggressive improvements for implementation with the remaining funds. These improvements are selected in BCR order.

Note that in all cases, it is possible for the model to identify a mandatory improvement for a section, and subsequently replace it with an economically more attractive improvement which corrects all the unacceptable conditions which existed on the section.

The identification of potential improvements to correct sections in unacceptable condition is discussed in section 4.2.3.5 "Addressing Unacceptable Conditions: the Optional First Pass" on page 4-15. The process of selecting mandatory improvements, or of replacing a mandatory improvement with a more aggressive improvement, is presented in paragraph section 7.12 "Selecting Mandatory Improvements" on page 7-19.

2.8 Implementation and Output

The condition of each section is maintained in a set of data items which are originally populated from the HPMS database. While many of these items are not changed during analysis (for example, section identification and location), others (such as traffic volume and pavement condition) can be expected to change with each passing funding period. Improvements are implemented through changes to applicable data items (notably pavement condition and number of lanes).

At the beginning of each funding period, the model forecasts the condition of each section at the end of the funding period. This basic forecast consists of predicting future traffic volume, then calculating the effect of this traffic on the pavement condition. For sections which are unimproved during the funding period, this becomes the condition of the section at the beginning of the subsequent funding period. Because HERS treats improved sections as receiving their improvements at the midpoint of the

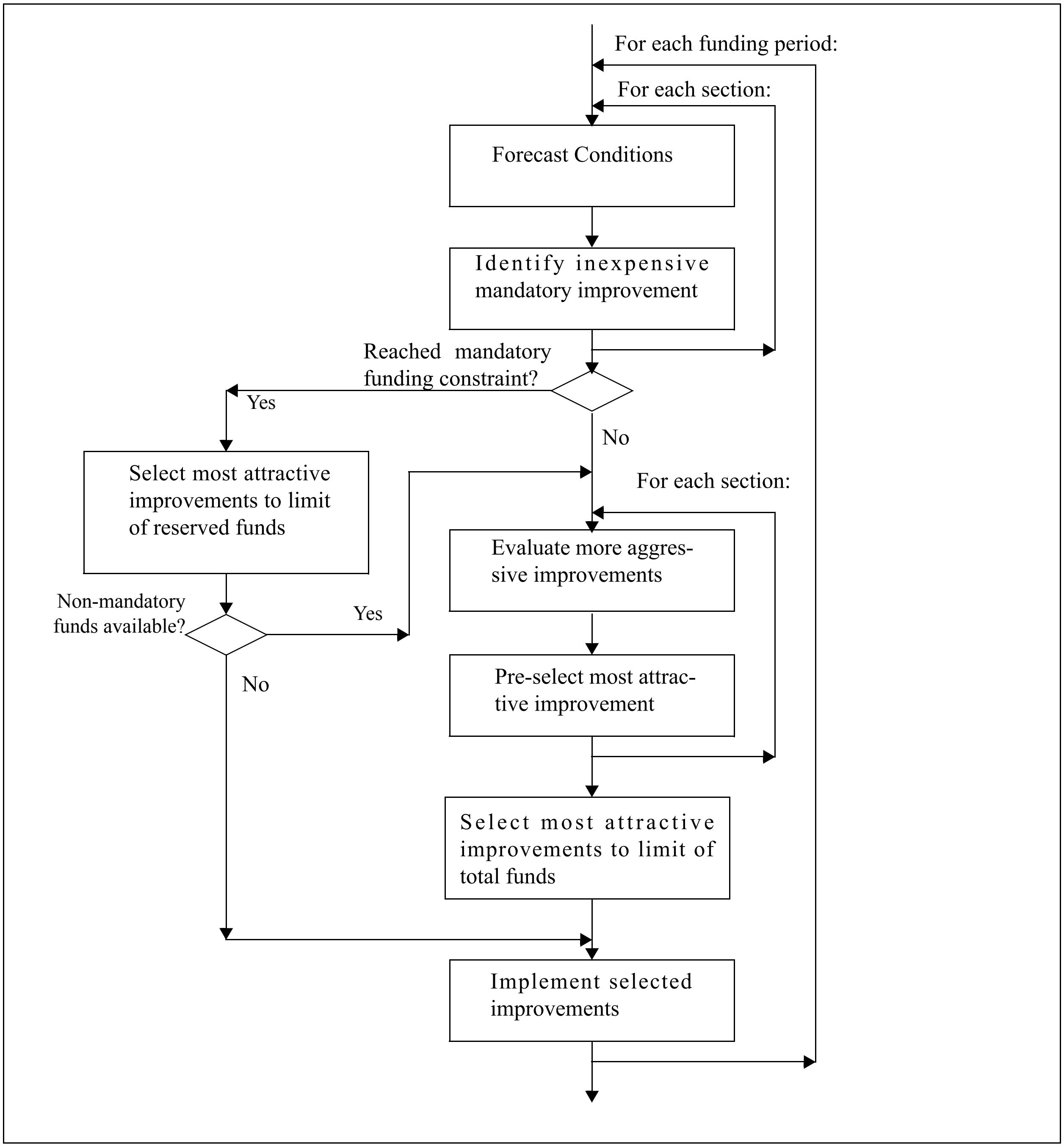

Figure 2-7. Constrained Fund Run With Mandatory Improvements

funding period, determining the end of period condition of an improved section consists of upgrading the section's condition to reflect the improvement and then forecasting it's condition at the end of the period.

At this point, the program accumulates the statistics which will be used to generate the output pages. See Chapter 8, "Model Output" for more details.

2.9 HERS Time Frames

The HERS program operates over a set of time frames known as funding periods (FPs), as shown in Figure 2-8 These funding periods are equal in length, and combine to form the overall analysis (OA) period. The set of all funding periods form a sequence, with the first one beginning at the start of the OA period, and each succeeding funding period starting at the end of the preceding one. HERS defines additional funding periods which start after the end of the OA period. These “post analysis period” funding periods are the same length as the funding periods within the OA period, and extend far enough beyond the end of the OA period to permit benefit-cost (B/C) analyses to be performed on all improvements that might be implemented during the OA period. Figure 2-8 depicts an overall analysis period consisting of four five-year funding periods.

HERS performs B/C analyses on all improvements that might be implemented during the OA period, but not on improvements that might be implemented after the OA period. For purposes of the B/C analyses, HERS treats all improvements as if they were implemented at the midpoint of the funding period. Accordingly, every benefit-cost analysis period (BCAP) extends from the midpoint of a funding period to the midpoint of a subsequent funding period (which can extend beyond the end of the OA period). Additionally, because of the impact of an improvement upon the price to the user of the section, the time-frame for the elasticity calculations (shown in the exhibit as ELAS) also run from funding period midpoint to funding period midpoint.

FP One	FP Two	FP Three	FP Four	FP Five	FP Six	
	BCAP	BCAP	BCAP	BCAP	BCAP	BCAP
	ELAS	ELAS	ELAS	ELAS	ELAS	ELAS
Overall Analysis Period				Post-Analysis Period		

0 2.5 5 7.5 10 12.5 15 17.5 20 22.5 25 27.5 30

Figure 2-8. HERS Time Periods

2.10 Functional Classes

The HERS program recognizes nine functional classes of highways, including all of the urban arterial and collector classes, and all of the rural arterial and major collector classes. Rural minor collectors and roads functionally classified as local are not recognized by HERS.

A large number of HERS parameters can be specified by the user with different values for each of the nine functional classes. Some of these items are:

- Deficiency Levels
- Serious Deficiency Levels
- Unacceptability Levels
- Minimum Tolerable Conditions
- Design Standards

- Improvement Costs
- Truck Growth Factors
- Cost of Non-Fatal Injuries
- Property Damage Cost per Crash
- Funds Available for Improvements (Fund Constrained Run)
- Highway Performance Goals (Performance Constrained Run)
- Weights for Highway Performance Goals
- Weights for Benefit-Cost Ratio Calculation.

The Fleet Composition model also relies on functional class. (See section 2.11 "The Fleet Composition Model" on page 2-15)

2.10.1 HERS Functional Class Groups

When performing a constrained fund run or a performance constrained run, HERS allows the user the options of setting separate budget constraints or performance goals for each functional class, or for certain combinations of functional classes. These combinations are shown in Table 2-2. The user can set targets for:

- 1 group (for all functional systems combined);
- 2 groups (for the urban system and for the rural system);
- 2 groups (for the principal arterials and for the minor arterials and collectors);
- 4 groups (for urban principal arterials, for rural principal arterials, for urban minor arterials and collectors, and for rural minor arterials and collectors); or
- 9 groups (for each of the nine functional classes distinguished by HERS).

The flow charts in Figure 2-4 through Figure 2-7 are based upon the standard case where the set of sample sections is treated as a single system (one group). However, if the user elects to use multiple functional class groups in setting performance goals or budget constraints, then during initialization, HERS takes the additional step of separating the sample sections into the component groups, and maintains a separate section file for each group. During processing, the model processes each group in turn in a loop nested between the loops for funding periods and sections. The structure then becomes:

```
Loop through each funding period...
    Loop through each functional class group...
        Loop through all sections in the class group...
            Process a section (forecast conditions, identify potential
            improvements, pre-select an improvement)
        End loop (all sections)
        Select improvements until constraint is satisfied for the class group
        Implement selected improvements for the class group
    End loop (functional class group)
```

Table 2-2. Highway Functional System Groupings

Code:	Description:	Single System	Rural and Urban	Princ. Art. & Other	Princ. Art. & Other by Rural/Urban	By Functional Class
	Number Of Groups >>>	**1**	**2**	**2**	**4**	**9**
	Rural					
01	Principal Arterial – Interstate	1	1	1	1	1
02	Other Principal Arterial	1	1	1	1	2
06	Minor Arterial	1	1	2	2	3
07	Major Collector	1	1	2	2	4
	Urban					
11	Principal Arterial – Interstate	1	2	1	3	5
12	Principal Arterial – Other Freeways and Expressways	1	2	1	3	6
14	Other Principal Arterials	1	2	1	3	7
16	Minor Arterial	1	2	2	4	8
17	Collector	1	2	2	4	9

End loop (funding period)

2.10.2 HERS-ST and Lower Functional Classes

HERS is not designed to handle rural minor collectors or sections on the two local functional systems. To allow states to analyze sections on these three systems, HERS-ST treats all sections on these systems as if they were rural major collectors or urban collectors, as appropriate. Accordingly, statistics printed by HERS-ST for rural major collectors actually include information for any rural minor collectors and rural local roads analyzed; and statistics for urban collectors similarly include information for any urban streets analyzed.

2.11 The Fleet Composition Model

HERS decomposes the vehicle fleet into three vehicle categories which include a total of seven vehicle types. These data on fleet composition are used by HERS when estimating speed, operating costs, travel-time costs, section capacity, and pavement deterioration. The progression from the entire fleet to the seven vehicle types is shown (proceeding from left to right) in Table 2-3

Table 2-3. Fleet Composition

Fleet	Weighting Factor	Vehicle Category	Weighting Factor	Vehicle Type
All Vehicles	Section data item: Percent Combination Trucks	Combination Trucks	Prorated from HPMS Vehicle Classification Study	Five or More Axle Combination Trucks
				Three/Four Axle Combination Trucks
	Section data item: Percent Single Unit Trucks	Single Unit Trucks	Prorated from HPMS Vehicle Classification Study	Three or More Axle Single Unit Trucks
				Six-Tire Trucks
	100% less percent of Single Unit and Combination Trucks	Four Tire Vehicles	Prorated from HPMS Vehicle Classification Study	Pickups & Vans
				Medium/Large Automobiles
				Small Automobiles

The fleet is divided into vehicle categories based upon section-specific percentages of the two truck classifications. These are reported in the HPMS input data record for each section. The four wheel category consists of the percentage of total traffic which is not part of either truck category. For the disaggregation of vehicle categories to vehicle types, HERS uses factors derived from the 1982 HPMS Vehicle Classification Case Study[1]. As shown in Table 2-4, these functional class dependent factors have been prorated to total 100 percent for each of the three categories.

Table 2-4. Fleet Disaggregation Factors

Functional Classes	Four Tire Vehicles			Single Unit Trucks		Combination Trucks	
	Small Autos	Med/Lg Autos	Pickups & Vans	Six-Tire Trucks	3+Axle SUTs	3-4 Axle Combos	5+ Axle Combos
Rural Interstate	.2365	.5367	.2268	.7372	.2628	.1023	.8977
Rural OPA	.1795	.5335	.2871	.7301	.2699	.1826	.8174
Rural Minor Arterial	.2081	.4762	.3156	.6404	.3596	.1675	.8325
Rural Major Collector	.1536	.4882	.3582	.6180	.3820	.2518	.7482
Urban Interstate	.2521	.5583	.1896	.7000	.3000	.1253	.8747
Urban Other Fwy/Exwy	.2521	.5583	.1896	.7000	.3000	.1253	.8747
Urban OPA	.2081	.5875	.2045	.7490	.2510	.1964	.8036
Urban Minor Arterial	.1976	.5998	.2027	.6590	.3410	.1765	.8235
Urban Collector	.2057	.5551	.2392	.6955	.3045	.3396	.6604

1. U. S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System Analytical Process *Technical Manual*, Version 2.1, December 1987, Table IV-20.

The HERS parameter file has entries for specifying the annual growth rate of the percentage of truck traffic for each functional class. This is applied to the section-specific percentages for the two truck categories to derive the new percentages for each category. For the 1997 Conditions and Performance Report the truck growth factors were set to 1.0 (i.e., no growth).

As an example of the weighted summation process used by HERS, let $VCAT_A$, $VCAT_{SU}$, and $VCAT_{CM}$ designate the three vehicle categories (four-tire vehicles, single unit trucks, and combination trucks), VT_1 through VT_7 correspond to the seven vehicle types, and FAF_1 through FAF_7 to the fleet disaggregation factors for each of the respective vehicle types (as shown in Table 2-4). After determining the quantity for each vehicle type (for example, travel time cost per 1000 vehicle miles), HERS calculates the quantity for each vehicle category weighted by vehicle type:

$$
\begin{aligned}
VCAT_A &= VT_1 \times FAF_{1_{fc}} + VT_2 \times FAF_{2_{fc}} + VT_3 \times FAF_{3_{fc}} \\
VCAT_{SU} &= VT_4 \times FAF_{4_{fc}} + VT_5 \times FAF_{5_{fc}} \\
VCAT_{CM} &= VT_6 \times FAF_{6_{fc}} + VT_7 \times FAF_{7_{fc}}
\end{aligned}
\qquad \textbf{\textit{Eq. 2.1}}
$$

Note that the fleet disaggregation factors are indexed by functional class. HERS next determines the percentages of single unit and combination trucks at the time of interest (t, in years) by applying the user-specified truck growth factor (*TRKFAC*) for the section's functional class to the percentages of average single unit (*PCAVSU*) and combination trucks (*PCAVCM*) reported in the section's HPMS data record:

$$
\begin{aligned}
PCSU &= PCAVSU \times TRKFAC_{fc}^{\ t} \\
PCCM &= PCAVCM \times TRKFAC_{fc}^{\ t}
\end{aligned}
\qquad \textbf{\textit{Eq. 2.2}}
$$

where *PCSU* and *PCCM* are the percentages at the time of interest. Finally, HERS produces a total weighted sum (*TWS*) combining the weighted values of the three vehicle categories:

$$
\begin{aligned}
TWS = {} & VCAT_A \times (1 \angle PCSU \angle PCCM) + VCAT_{SU} \times PCSU \\
& + VCAT_{CM} \times PCCM
\end{aligned}
\qquad \textbf{\textit{Eq. 2.3}}
$$

2.12 Policy Alternatives

Although HERS is primarily oriented toward evaluation of investment in highway improvement projects, the model can also estimate the impacts of several policy alternatives.

2.12.1 Funding Constraints

Limited funds for capital investment is a necessary condition for investment decisions, and HERS allows for funding caps by funding period and by functional class groupings. Constrained funding can also be modeled by adjusting the minimum BCR threshold until the HERS-recommended spending meets the budget constraint; this method then reveals the level by which worthwhile projects are not implemented. For additional information see section 2.10.1 "HERS Functional Class Groups" on page 2-14, section 2.7.1 “The Improvement Selection Procedures” on page 2-7, and section 7.11.2 “Constrained Analysis” on page 7-15.

2.12.2 Fuel Taxes

The price of fuel (gasoline and diesel) is entered exclusive of federal and state excise taxes or local sales taxes. Separately, a value for fuel taxes in dollars per gallon is entered. This value is included in the price of travel to the user (therefore affects traffic volume through the demand elasticity) but is not included in benefits (from society’s viewpoint, the tax is a transfer).

2.12.3 Maximum Number of Lanes/High Cost Lanes

As a policy option, the user can specify the maximum number of lanes permitted on sections of each functional class. If the existing number of lanes exceeds this maximum, lanes will not be removed to meet the cap, but HERS will not add lanes in excess of the limit. The cap might be interpreted in some circumstances to represent corridor capacity, such as with parallel freeways.

The user may also specify, by functional class, an override value applied to each section’s widening feasibility code. Where the section data indicate that widening is not feasible, this override can be applied to allow adding lanes at a higher cost. The cost can be specified by the user. This option might allow for double-decking or parallel facilities. For details, see section 4.2.4 “Effects of HERS Improvements” on page 4-20 and section 4.3 “The Widening Feasibility Model” on page 4-26.

The user can also specify the maximum number of normal cost lanes permitted on sections of each functional class. Any lanes added on a section in excess of this limit are added at high cost without regard to the section’s widening feasibility code.

Chapter 3:

Inputs

HERS' inputs are broadly divided into two groups. The first group is section-specific data which define the attributes of individual highway sections. This group can be further divided into the descriptive attributes contained in the HPMS sample section records and the prescriptive attributes contained in the user-specified improvement file. The second group consists of that wide range of parameters which are not specific to individual highway sections. This second group is further divided into control data, which govern the overall analysis, and parameter data, which is used by the internal sub-models' various processes.

This chapter also addresses the processing performed by the HERS PreProcessor. The basic function of this software is to transform the comma-delimited input file into a binary file for subsequent processing by the HERS model. It also performs some reasonableness checks, converts units and codes, calculates additional section-specific values needed by HERS, and pre-processes the user-specified improvement file.

The HERS-ST graphical user interface (GUI) functions as an intermediary between the HERS-ST user and the HERS executables and parameter files. The GUI provides tools to manipulate section data, control data, and program parameters. The GUI invokes both the PreProcessor and the HERS engine and collects the output for generation of reports, graphs, and maps. See the HERS-ST User's Guide for detailed information on using the GUI.

This chapter addresses the inputs as received by the HERS engine and the PreProcessor. It also discusses several basic HERS topics.

3.1 Section Data

Each highway section represents a potential improvement project. Whatever information HERS is provided with about the individual section (pavement condition, length, etc.) is contained in the section data for that section.

3.1.1 HPMS Sample Section Data Items

HERS accepts section data in the HPMS comma-delimited format. Although HERS does not use all the HPMS fields, the unused fields must still be marked by a comma. The individual fields should be coded as described in the HPMS Field Manual of December, 2000.

Table 3-1 presents the HPMS data items used by HERS. Each HPMS item is identified by HPMS item number. Item numbers not listed in Table 3-1 are not used by

HERS. The "Editing" column may summarize edits performed by the PreProcessor or refer the reader to paragraphs describing the edit process in greater detail.

Table 3-1. HPMS Data Items Used by HERS

HPMS Item No.	Variable Name	Description	Editing by HERSPP
1	YR	Year	
2	STATE	State FIPS code	
3	UNITS	Reporting unit (English or metric)	from "0=eng, 1=metric" to "1=eng, 2=metric"
4	CNTY	County code	Alaska conversion, see section 3.3.4.2
5	SECTIONID	Section identification	
8	SCF	State control field	
10	LRSID	LRS Identification	
11	BEGMP	LRS beginning mile point	
12	ENDMP	LRS end mile point	
13	RURURB	Rural/urban designation	HERSPP validates against FC (see 3.3.1.2)
17	FC	Functional class	see 3.3.1.3
18	GFC	Generated functional class code	
20	UNBLT	Unbuilt facility code	section skipped if unbuilt
27	FT	Facility type (one- or two-way)	section skipped if structure
30	SLEN	Section length	metric/English conversion, see 3.3.4.5
33	AADT	Annual average daily traffic	
34	TLANES	Number of through lanes	
35	IRICOD	International roughness index	metric/English conversion, see 3.3.4.5; conversion to PSR, see 3.3.4.6
36	PSR	Pavement condition	unpaved default value, see 3.3.2.1; paved default value, see 3.3.2.2
37	HOV	HOV operation code	
47	SECNUM	HPMS sample identifier or other section identifier	
49	EXPFAC	Expansion factor for standard HPMS sample	
50	SURF	Surface type	converted to HERS codes: see 3.3.4.4
51	SNORD	Structural number or Depth	unpaved default, see 3.3.2.1; metric/English conversion, see 3.3.4.5; calculated, see 3.3.3.1
52	CLIMATE	Climate zone	
53	IMPYR	Year of surface improvement	
54	LANEW	Lane width	metric/English conversion, see 3.3.4.5
55	ACCESS	Access control code	

Table 3-1. HPMS Data Items Used by HERS

HPMS Item No.	Variable Name	Description	Editing by HERSPP
56	MEDT	Median type code	
57	MEDW	Median width	metric/English conversion, see 3.3.4.5
58	SHLDT	Shoulder type code	converted to HERS codes: see 3.3.4.3
59	RSHLDW	Right shoulder width	metric/English conversion, see 3.3.4.5
60	LSHLDW	Left shoulder width	metric/English conversion, see 3.3.4.5; non-divided highways, see 3.3.2.2
61	PKPARK	Peak parking code	
62	WDFEAS	Widening feasibility code	
63 - 68	LCURVE(I)	Curves by class	total curve length, see 3.3.1.5; metric/English conversion, see 3.3.4.5
69	HORALN	Horizontal alignment adequacy code	optional recalculation, see 3.3.3.9
70	TERRN	Type of terrain	urban code default, see 3.3.2.2
71	VERALN	Vertical alignment adequacy code	optional recalculation, see 3.3.3.9
72-77	LGRADE(I)	Grades by class	total grade length, see 3.3.1.5; metric/English conversion, see 3.3.4.5
78	PSD	Percent passing-sight distance	
79	WDS	Weighted design speed	re-calculated, see 3.3.3.5
80	SPDLIM	Posted speed limit	enforces maximum speed, see 3.3.1.6; metric/English conversion, see 3.3.4.5
81	PCPKSU	Percent peak single-unit commercial vehicles	percentage conversion, see 3.3.4.1
82	PCAVSU	Percent average daily single-unit commercial vehicles	percentage conversion, see 3.3.4.1
83	PCPKCM	Percent peak combination commercial vehicles	percentage conversion, see 3.3.4.1
84	PCAVCM	Percent average daily combination commercial vehicles	percentage conversion, see 3.3.4.1
85	KFAC	K-Factor	percentage conversion, see 3.3.4.1; validation, see 3.3.1.7
86	DFAC	Directional factor	percentage conversion, see 3.3.4.1; validation, see 3.3.1.7
87	PLANES	Number of peak lanes	
88	LTURN	Turning lanes - left	urban validation, see 3.3.1.10
89	RTURN	Turning lanes - right	urban validation, see 3.3.1.10
90	SIGTYP	Prevailing signalization type code	signalization validation and override, see 3.3.1.11
91	PCTGRN	Percent green time	percentage conversion, see 3.3.4.1; validation, see 3.3.1.8

Table 3-1. HPMS Data Items Used by HERS

HPMS Item No.	Variable Name	Description	Editing by HERSPP
92	NSIG	Number of intersections with traffic signals	enforces maximum number of traffic control devices per mile, see 3.3.1.9
93	NSTOP	Number of intersections with stop signs on sample section	enforces maximum number of traffic control devices per mile, see 3.3.1.9
94	NOINTS	Number of other intersections	
95	CAPAC	Peak capacity (peak direction)	optionally re-calculated, see 3.3.3.6
97	FAADT	AADT in future year (FADTYR)	default if zero and maximum rate, see 3.3.3.7.4
98	FADTYR	Future year for AADT forecast	default if zero, see 3.3.3.7.4

3.1.2 User-Specified Improvements Data File

The HERS-ST user may specify improvements to be implemented on individual sections at pre-determined times. (This capability is not available with the national version of the HERS model.) The improvements are contained in a comma-delimited text file which the PreProcessor converts to a binary file for subsequent implementation by the HERS executable. The HERS-ST GUI includes tools for generating, modifying, and maintaining the text file, or users may elect to construct it manually.

The input file consists of a variable-length record for each section being improved. Table 3-2 shows the nine fields which comprise the file. The first field declares the number of improvements defined for the section (and thus the length of the record). The second and third fields identify the section, and correspond to HPMS input fields 4 (County) and 47 (Sample ID). The fourth through ninth fields pertain to an individual improvement, and are repeated for each improvement defined for the section. (Thus, a record which specified two separate improvements would consist of fields 1 through 3, then 4 through 9 to define the first improvement, and 4 through 9 again defining the second improvement.)

Table 3-2. User-Specified Improvement Input Fields

Field			GUI Column Name	Format
1.	Number of Improvements		Improvements	integer
2.	County Code		County	integer
3.	Sample Identifier		SampleID	alphanumeric
4.	Year of Improvement		SFn_Year	integer
5.	Type of Improvement		SFn_ImpTyp	integer
6.	Override Flag		SFn_Ovrd	integer
7.	Cost of Improvement		SFn_ImpCst	floating point
8.	Lanes To Add		SFn_LaneAdd	integer
9.	Increase in Capacity		SFn_IncCap	integer

3.2 HERS Control and Parameter Variables

In addition to the section-specific data files, HERS and the HERS PreProcessor accept three additional files of processing parameters plus two files containing control variables. Broadly speaking, the two control files (one each for HERS and the PrePro-cessor) contain processing directives which are likely to be specific to an individual analysis run, while the parameter files contain data which are more likely to be unchanged between runs. The HERS-ST GUI does not require the user to be aware of these separate control files when operating the GUI under standard mode, and pre-sents the various control parameters to the user without indicating that they belong to individual files controlling distinct programs.

Two of the parameter files are focused on specific themes. The improvement cost file (IMPRCOST.DAT) contains data items which define the costs of improving highway sections: it's contents are discussed below and their use is explicated in Chapter 6. The deficiency level tables file (DLTBLS.DAT) defines the various condition levels which will prompt HERS to analyze a section for possible improvement. Chapter 4 discusses the use of these criteria, which are listed, with their default values, in Appendix A, "Default Deficiency Criteria Tables." The third parameter file (PARAMS.DAT) contains parameters covering the breadth of the HERS modelling process: the pavement model, operating cost components, the speed model, and the safety model, to name but a few. This report addresses these specific parameters when discussing the various internal models and processes.

3.2.1 The Preprocessor Control Inputs

Table 3-3 :presents the inputs to the PreProcessor. These are passed in the file PPSPEC.DAT. The columns in the table are:

- Control Input - the acronymic name of the data item;
- Available via GUI - whether or not the data item is presented to users of the HERS-ST GUI using standard mode (all data items are available using advanced mode); and

Table 3-3. PreProcessor Control Inputs

Control Input	Available via GUI?	Description
FILIN	No[a]	Name of section data file (see section 3.1.1)
FILOUT	No	Binary section file name
DSTOUT	No	Distribution file name
HPMSF	No	HPMS format flag
BASEYR	Yes	Base year of analysis
PSRUPS	Yes	PSR for unpaved sections (see 3.3.2.1); passed to HERS as lower limit of pavement deterioration.
CALCCAP	No	Coded capacity override switch (see 3.3.3.6)
MAXGRW	Yes	Maximum AADT growth rate (see 3.3.1.4)
GRSWITCH	No	Governs treatment of excessive growth rate (see 3.3.1.4)
DEFGRW	No	Default AADT growth rate (see 3.3.1.4)
PGTMAX	No	Maximum percent green time (see 3.3.1.8)
PGTMIN	No	Minimum percent green time (see 3.3.1.8)
PGTRUR	No	Table of default percent green time (see 3.3.1.8)
MAXR	Yes	Maximum AADT/Capacity ratio (see 3.3.3.6)
MRERR	Yes	Report excessive AADT growth rate switch
MAXTCD	No	Maximum number of traffic control devices per mile (see 3.3.1.9)
NTDERR	No	Governs generation of traffic control device error messages
MAXSPL	Yes	Maximum speed limit
RUERR	No	Governs generation of *FC* and *RURURB* error messages
AASWITCH	No	Alignment adequacy calculation switch (see 3.3.3.9)
PLERR	No	Peak lanes error reporting switch
PSRIRI	Yes	PSR/IRI selection switch
OVERIDEMODE	Yes	Implement user-specified improvements switch
STATEIN	No[a]	Name of user-specified improvement file
STATEOUT	No	Name of binary user-specified improvement file

a. Although the user does not specify the name of the file, selects the file from those available within the current project.

- Description - a brief description of the input and a reference to further reading.

3.2.2 The HERS Control Inputs

Table 3-4 presents the inputs to the HERS executable. These are passed in the file PPSPEC.DAT. The columns in the table are the same as for the PreProcessor inputs of Table 3-3.

Table 3-4. HERS Control Inputs

Control Input	Available via GUI?	Description
RUNNUM	Yes	Sixteen character run identifier
RUNDES	Yes	Run description
FILOVR	No	Input file overwrite switch
FILDEL	No	End-state file deletion switch
FILIN	No	Binary section file name
STATEIMPS	No	Binary user improvement file name
DISTIN	No	Distribution file name
FILOUT	Yes	Output text file name
LFP	Yes	Length of funding period
NFP	Yes	Number of funding periods
AADTTY	Yes	Type of AADT growth
INPUTLRS	Yes	Long run share of elasticity
INPUTSRE	Yes	Short run elasticity
DRATE	Yes	Discount rate
BACKLG	Yes	Backlog switch
IMPRST	Yes	Governs printing of user improvement information
WARNMSI	No	Governs user improvement warning message generation
WARNMSG	No	Directs user improvement warning messages
MAXNTD	No	Maximum number of traffic control devices per mile
MNDIMP	Yes	Mandatory improvement switch
NEEDS	Yes	Full engineering needs switch
BCRMIN	Yes	Minimum BCR
OBJCTV	Yes	Analytical objective
MCC	Yes	Maintain current conditions switch
CSPEC	Yes	Constraint specification selector
SCVALU	Yes	Table of fund/performance constraints

Table 3-4. HERS Control Inputs

Control Input	Available via GUI?	Description
NMFNDS	Yes	Table of funds reserved for non-mandatory improvements
AIUNIT	Yes	Units of funds for aggressive improvements
CWT	Yes	Constraint weights
MCUNIT	Yes	Maintenance cost units
BCRWT	No	Benefit-cost ratio weights
OUTPUT	Yes[a]	Table selects output text pages
SCFACT	Yes	Output scale factors
PPDUNITS	No	Peak period delay units
NPSEC	No	Sections processed interval
NSIMP	No	Improvements selected interval

a. The HERS-ST GUI provides control over a subset of the text output pages.

3.2.3 Parameter Inputs

HERS uses three input parameter files, one each for improvement costs, deficiency levels, and general parameters. The PreProcessor uses the deficiency levels file and the general parameter files. The GUI ensures that the same files used for the PreProcessor are used for the main HERS program.

3.2.3.1 IMPRCOST.DAT – the Improvement Cost File

HERS uses the costs in this file to calculate the cost of section improvements. All the fields of this file are available through the GUI.

The file consists of one column for each of the nine elemental improvement costs, and twenty-one rows corresponding to highway group. Table 3-5 presents the elemental cost columns.

Table 3-5. Elemental Improvement Cost Columns

Column	Column Label	Improvement Cost
A	RECON W-LAN	Cost to reconstruct and widen existing lanes
B	RECON PAVE	Cost to reconstruct existing lanes
C	RESURF W-LAN	Cost to resurface and widen existing lanes
D	RESURF PAVE	Cost to resurface existing lanes
E	IMPRV SHLD	Incremental cost to improve shoulder (one side)
F	ALANE NORM	Incremental cost to add lane at normal cost
G	ALANE HIGH	Incremental cost to add lane at high cost
H	ALGN NORM	Cost to realign all lanes at normal cost
I	ALGN HIGH	Cost to realign all lanes at high cost

For calculation of improvement costs, HERS uses seven highway classifications, each of which is subdivided into three groups. The four rural classifications correspond to the four rural functional classes:

- Interstate;
- Other Principal Arterial;
- Minor Arterial; and
- Major Collector.

Within each rural classification sections are further divided by terrain type:

- Flat;
- Rolling; or
- Mountainous.

Urban sections are divided into three classifications:

- Interstate and Principal Arterials - Other Freeways and Expressways;
- Other Principal Arterials; and
- Minor Arterials and Collectors.

Within each of these urban classifications, sections are divided by urbanized area:

- Small Urban;
- Small Urbanized; or
- Large Urbanized.

See Chapter 6 for details of how HERS calculates the costs of improvements.

3.2.3.2 DLTBLS.DAT – the Deficiency Levels File

The DLTBLS.DAT file contains deficiency and design standard parameters. It also contains user-specified thresholds used in generating output statistics. Table 3-6 presents the deficiency level entries from the beginning of the DLTBLS.DAT file.

As indicated in Table 3-6, the deficiency level and user-specified threshold entries (*DL* and *UST1*) are available via the GUI (on the Deficiency Thresholds page of the Parameter Data interface). The remaining items can be accessed through the Advanced Mode.

For the categories shown in Table 3-6, the rural sections are differentiated by functional class, terrain type, and (except for Interstates) by volume groups. Urban sections are differentiated by functional class except for the two alignment categories: for horizontal alignment, HERS requires entries for Interstates, Other Freeways, and OPAs; there are no entries for urban vertical alignment. Also, there are no design standard (*DS*) entries for urban sections for these three categories: surface type, lane width, and right shoulder width – they are included in the second part of DLTBLS.DAT where the sections are grouped differently.

Table 3-6. Deficiency Level Tables in DLTBLS.DAT

Attribute and (Units)	Deficiency Level Column Headings	Available through GUI?	Description
Pavement Condition (IRI)	UST1	N	User Specified Thresholds used for output statistics only
	UST2	N	
	UST3	N	
	UST4	N	
	UST5	N	
Pavement Condition (PSR)	UL	N	Unacceptability Level
	RL	N	Reconstruction Level
	UST1	Y	User Specified Threshold used for output statistics only
	UST2	N	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level
Surface Type (HERS Surface Type codes; *see* 3.3.4.4)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level
	DS	N	Design Standard
V/C Ratio (V/C Ratio)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level
	WS	N	Widening Standard
Lane Width (feet)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level
	DS	N	Design Standard
Right Shoulder Width (feet)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level
	DS	N	Design Standard

Table 3-6. Deficiency Level Tables in DLTBLS.DAT

Attribute and (Units)	Deficiency Level Column Headings	Available through GUI?	Description
Shoulder Type (HERS Shoulder Type codes, see 3.3.4.3)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics and minimum shoulder type after reconstruction
	DL	Y	Deficiency Level
Horizontal Alignment (HPMS Horiz. Alignment Adequacy Code)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level
Vertical Alignment (HPMS Vert. Alignment Adequacy Code)	UL	N	Unacceptability Level
	SDL	N	Serious Deficiency Level
	UST1	Y	User Specified Threshold used for output statistics only
	DL	Y	Deficiency Level

The second part of the DLTBLS.DAT file contains additional design standard entries. These entries are available through the GUI using the Advanced Mode. The entries in this second part of the file are presented in Table 3-7.

Table 3-7. Additional Design Standards in DLTBLS.DAT

Design Standard	Units	Rural Section Groups	Urban Section Groups
Curve Categories	HPMS Curve Classes	By functional class by terrain	By Interstate, Other Freeway, and OPA
Grade Categories	HPMS Grade Classes	By functional class by terrain	(None)
Lane Width	Feet	(None)	By Freeway/Expressway by Design; Other Divided; Undivided Arterials; and Undivided Collectors
Shoulder WIdth	Feet	(None)	By Freeway/Expressway by Design; Other Divided; Undivided Arterials; and Undivided Collectors
Surface Type	HERS Surface Type code	(None)	By Freeway/Expressway by Design; Other Divided; Undivided Arterials; and Undivided Collectors

For the discussion of HERS' use of deficiency criteria, see paragraphs 4.2.1 and 4.2.2. The application of design standards to improved sections is addressed in paragraph 4.2.4.

3.2.3.3 PARAMS.DAT – the Parameter File

The PARAMS.DAT file contains the balance of HERS input parameters. The first two lines are used to identify the specific file. The bulk of the entries are grouped into ten topics, each of which is addressed below. These in turn are followed by several groups of arcane parameters (beginning with *TRISF*, the travel rate index scale factor) which apply only to the national version of the model, have no effect on the operation of HERS-ST, and so are not described here.

Only a few of the parameters in PARAMS.DAT are available through the GUI. Unless specifically noted in the text, these parameters can only be modified using Advanced Mode.

3.2.3.3.1 Pavement Improvement Parameters

This is a loosely focused set of parameters which appear in two locations in the file: at the very beginning (right after the file identification) and further down under the heading "For PAVIMP subroutine." Most of the parameters available through the GUI are part of this group. These parameters are:

- *DP* – Design period, in years, available through the GUI;
- *WDFOVR* – Widening feasibility override, specified for each functional class using the widening feasibility codes (see Table 4-8), available through the GUI;
- *MAXLNS* – Maximum number of lanes, by functional class, available through the GUI;
- *PAVMTH* – Thickness of new pavement, in inches, by ESAL range limits (from *RNGLIM* entries) for a) all reconstruction or resurfacing of flexible pavement, and b) resurfacing of rigid pavement;
- *PSRREC* – PSR after reconstruction, for each of four pavement types (high flexible, high rigid, medium, and low) for rural and urban, available through the GUI;
- *PSRINC* – Increase in PSR after resurfacing, for each of four pavement types (high flexible, high rigid, medium, and low) for rural and urban, available through the GUI;
- *PSRRMX* – Maximum value of PSR after resurfacing, for each of four pavement types (high flexible, high rigid, medium, and low) for rural and urban, available through the GUI;
- *RNGLIM* – Range limits for design number of ESALs, in thousands of ESALs, five entries defining six ranges; and
- *NEWSNC* – Coefficients for calculating new structural number (*SN*) after improvement using Equation 4.1.

3.2.3.3.2 Truck Growth Factors

This three line entry specifies the annual growth rate of trucks as a portion of total traffic on all sections in each functional class. The factor is applied to the average percent of single unit trucks and the average percent of combination trucks (HPMS data items 82 and 84) when forecasting future traffic volumes. This factor does not directly affect the traffic volume, but only the average percentages of the two truck groups.[1]

3.2.3.3.3 Operating Cost Parameters

This section of PARAMS.DAT establishes values for the five components of operating costs:

- fuel consumption
- oil consumption
- tire wear
- maintenance and repair
- depreciable value.

The section contains two sets of entries. The first set specifies the Efficiency Adjustment Factors for each of the components. These entries represent changes in the consumption of resources by the vehicle fleet since 1980. See paragraph 5.2.1.2, “Adjustment Factors for Consumption Rates,” for a detailed discussion.

The second set of entries is for the unit prices of the five components. These are discussed in paragraph 5.2.1.1, “Component Prices.”

For both sets of entries, HERS requires separate values for each of the seven vehicle types.

3.2.3.3.4 Fuel Excise Tax Parameters

This short section begins with entries of the fuel tax for each of the seven vehicle types. Entered in dollars per gallon, this is the fuel tax at the beginning of the analysis period. The next four lines are for factors altering the fuel tax during the course of the analysis beginning with the first funding period.

3.2.3.3.5 Speed and Congestion Parameters

These parameters are found in two places in the PARAMS.DAT file. The first group is designated as “For APLVM subroutine,” the second group is near the end of the file and is labeled “For CONGFWAY and CONGSigArt subroutines.”

The APLVM group consists of variables HERS uses to calculate the effect of pavement roughness on speed, as presented in paragraph 5.4.1.2. The four input values are:

- *VR1* – Speed limited by roughness at PSR of zero;
- *VR2* – Speed limited by roughness when PSR is equal to *PSRB*;
- *PSRB* – PSR value above which the speed limited by roughness is determined by *VRSLOP*; and

1. Note that the change in traffic composition may have a small effect on volume due to the application of demand elasticity.

- *VRSLOP* – Slope of speed limited by roughness above *PSRB*.

The congestion group consist of three entries:

- *BPM* – Bottlenecks per mile, one value each for freeways and signalized arterials;
- *INCFAC* – incident rate factor to reflect the effects of policy to reduce incident rates, one value each for freeways and signalized arterials; and
- *SIGADJF* – Signal timing adjustment factor, four values corresponding to the four *SIGTYP* codes.

3.2.3.3.6 Price Indices

The price indices are the mechanism used to align various input values, expressed in dollars of a specific year, with the single dollar-year HERS uses to perform its cost, benefit, and price calculations. This is typically the base year of the analysis period corresponding to the description of the highway system contained in the section data file. Although HERS discounts future benefits and costs using the user-supplied discount rate (*DRATE*), HERS does not support fluctuations in the value of the dollar but conducts all evaluations using constant dollars.

There is a wide variety of dollar-valued inputs to HERS (improvement costs, vehicle maintenance costs, costs of crashes, etc.) which are specified in a wide range of dollar-years. This is sometimes a reflection of the data used in the original research that became the basis for the model incorporated into HERS, and sometimes of the most recent publication of the statistics used to generate the HERS inputs.

Table 3-8, "Price Indices Used by HERS," presents a list of sources used in indexing HERS prices and costs on a national basis.

3.2.3.3.7 Pavement Deterioration Parameters

These parameters, labelled in the file as belonging to the FORCST routine, affect the model's calculation of pavement deterioration. This first group of parameters affects the limits of the PSR deterioration procedure.

- *PDRAF* – The pavement deterioration rate adjustment factor, entered separately for rigid and flexible pavements, is a gross adjustment applied to the deterioration due to accumulated ESALS.
- *MAXPD* – The maximum pavement deterioration rate, entered in PSR per year, places an upper limit on the rate of pavement deterioration.
- *MAXLFE* – The maximum pavement life , entered by pavement section and rigid/flexible pavement, is used in enforcing a lower limit on pavement deterioration (that is, in ensuring that pavement deteriorates enough each year that it will not outlive its maximum projected life).

HERS uses the second group of parameters in calculating the effect of accumulated ESALS on pavement deterioration.

- *SO* – Prediction error, for flexible and rigid pavements;
- *REL* – Reliability factor, for interstate, other arterials, and collectors;

Table 3-8. Price Indices Used by HERS

Parameter	Nominal Base Year	PARAMS.DAT Price Index	PARAMS.DAT Line	Applicable Index
Cost of Fuel	2002	Cost of Fuel	45	
Cost of Oil	1995	Cost of Oil	46	
Cost of Tires	1995	Cost of Tires	47	
Cost of Maintenance	1995	Cost of Maintenance and Repair	48	
Depreciable Value	1995	Cost of Vehicle	49	
Fuel Excise Tax	2002	Fuel Excise Tax	50	
Rural Improvement Costs	2002	Improvement Costs, Rural	51	
Urban Improvement Costs	2002	Improvement Costs, Urban	52	
Highway Maintenance Costs – internal (*see* Table 5-31, “Maintenance Costs for Flexible Pavements”)	1988	Highway Maintenance Costs, Rural *and* Highway Maintenance Costs, Urban	53 *and* 54	Office of Program Administration, *Price Trends for Federal-Aid Highway Construction*, U.S. Department of Transportation, Federal Highway Administration, Washingon, D.C., quarterly
	2000	Value of Time	55	
	1995	Vehicle Costs	56	
	2000	Inventory Costs	57	
	2001	Value of Life	58	
	2000	Injury Costs	59	
	2000	Property Damage Costs	60	
	2000	Crash Delay Costs	61	
	Align-men			

- *MR* – Modulus of resistance;
- *PT* – Design terminal servicability index;
- *SCP* – Modulus of rupture;
- *CD* – Load transfer coefficient;
- *J* – Drainage coefficient;
- *EC* – Modulus of elasticity; and
- *K* – Modulus of sub-grade reaction.

See paragraph 5.1.2, “Pavement Condition,” for details and usage of these parameters.

3.2.3.3.8 Safety Parameters

The input parameters used by the safety model consist of three groups: dollar-valued damage parameters; fatality and injury to crash ratios; and parameters defining the physical properties of sections.

It’s a good idea, when changing thess dollar-valued parameters, to note the year of the dollar used in the comment portion of the file:

- *VLIFE* – Value of life, used in conjunction with fatalities;
- *INJCST* – Injury cost, for each functional class;
- *PROPDM* – Property damage, for each functional class.

The crash ratios correspond to a specific year, and can be set to decline:

- *FATR* – Fatality/crash ratio by functional class, govern the number of fatalities per crash;
- *INJR* – Injury/crash ratio by functional class, specifies the number of injuries per crash;
- *FICRYR* – Specifies the base year for the ratios;
- *APDFPC* – Annual percentage decline in fatalities in per crash beginning in *FICRYR*;
- *APDIPC* – Annual percentage decline in injuries per crash beginning in *FICRYR*; and
- *APDCR* – Annual percentage decline in crash rates beginning in 1995.[2]

The following safety parameters relate to the physical characteristics of sections:

- *DDRML* – Driveway density for rural multilane sections;
- *RHRRML* – Roadside haard rating for rural multilane sections;
- *MAXIML* – Maximum number of intersections per mile on rural multilane sections;
- *MINSPM* and *MAXSPM* - Minimum and maximum number of signals per mile on urban multilane sections; and
- *PDEVEL* – Probability that rural road is in area of dense development, entered for three road types: two lane, multilane undivided, and multilane divided.

All of the following parameters relate to the physical characteristics of rural two lane sections, and follow the “For R2LANE subroutine” heading in the file:

- *DD* – Driveway density;
- *MAXIR2* – Maximum number of intersections per mile;

2. The crash rates are hardcoded and reflect 1995.

- *CCGR* – Crest curve grade rate, entered for each of the three terrain types: level, rolling, and mountainous (as per HPMS item number 70);
- *RHR* – Roadside hazard rating;
- *RHR3LI* – Roadside hazard rating for three-legged intersections;
- *PRTL* – Probability that a three-legged intersection has a right turn lane; and
- *ADJIA* – Adjusted intersection angle.

3.2.3.3.9 Travel Time Cost Parameters

Under the heading "For TTCOST subroutine" are five entries HERS uses to determine the cost of travel time per hour:

- *TTCPPH* – Travel time cost in dollars per person hour, entered for each of the seven vehicle types (see paragraph 2.11, "The Fleet Composition Model");
- *VDEPPH* – Hourly vehicle depreciation costs, entered for each vehicle type;
- *INVCPH* – Inventory cost per hour, with entries for each vehicle type[3];
- *AVO* – Average vehicle occupancy, entered for each vehicle type; and
- *DINCCR* – The ratio of the value of incident delay to the value of travel time, this entry (when greater than one) exacts an additional travel time penalty when traffic is slowed due to crashes.

For more detail, see paragraph 5.5, "Travel Time Costs."

3.2.3.3.10 State Cost Factors

The section of state cost factors in PARAMS.DAT breaks with the usual format of the file in which the parameter values are at the left of the line and the descriptive comments are on the right of the line. This section presents four columns, of which only the second (*SCF* for state cost factor) is a parameter value, and the other three (FIPS code, Region, and State) are not read by the model. The SCF is used to accomodate differences between the national average improvement costs and the prevailing cost of improvements in each state or jurisdiction.

3.3 The HERS Preprocessor

The HERS PreProcessor is a separate program which prepares the HPMS section record data for processing by the HERS program proper. The PreProcessor's primary functions are

- Perform validation checks on specific fields of the HPMS input data;
- Provide default values when the input data is missing or inappropriate;

3. The supplied values for inventory costs are set to zero for all vehicle types except for combination trucks.

- Alert user to sections with values beyond specified bounds;
- Convert certain HPMS codes to HERS codes;
- Convert, as indicated, metric units to English units of measure, and IRI to PSR;
- Calculate section-specific values needed by HERS but not present in the HPMS data;
- Process user-specified improvements for implementation by the HERS model;
- Produce two binary output files (one of section data, the other of user-specified improvements) for use by the HERS model.

HERS-ST users do not interface directly with the PreProcessor: the HERS-ST GUI invokes the PreProcessor automatically prior to executing the main HERS program. The HERS-ST GUI prepares the inputs for the PreProcessor from the control, parameter, highway, and improvement models specified by the user.

3.3.1 Validations

The HERS PreProcess corrects input data that shows invalid or inconsistent codes.

3.3.1.1 Sections Skipped by HERSPP

HERSPP "skips" certain sections by not writing a section record to the binary file for use by HERS. HERSPP skips the following sections:

- Local sections (with generated functional class code set to 6)[4];
- Rural minor collectors (functional class code equal to 8)[4];
- Unbuilt sections (when the Unbuilt field is greater than 1);
- Structures (when the facility code is greater than 2);
- Sections with the rural/urban designation input as zero;
- Sections with the functional class input as zero;
- Sections with the section length input as zero;
- Sections with the initial AADT input as zero; and
- Sections with the expansion factor input as zero.

HERSPP reports the number of sections skipped.

3.3.1.2 *RURURB* Validation

HERSPP checks the Rural/Urban designation against the functional class. If a section's functional class code is greater than 10 and the rural/urban designation is set to 1 (rural area), it is reset to 4 (large urbanized area). If a section's functional class code is less than 10 and the rural/urban designation is greater than 1, it is reset to 1.

3.3.1.3 Functional Class Validation

If a section's functional class (*FC*) is input as 13 or 15, HERSPP resets the *FC* to 12 or 14, respectively.

4. The HERS-ST GUI resets the functional class codes for these sections to either rural major collectors or urban collectors, as appropriate, before passing the section data to the PreProcessor.

If a section's *FC* remains invalid, and the generated functional class code (*GFC*) and rural/urban designation are valid, then HERSPP sets the *FC* as shown in Table 3-9.[5]

Table 3-9. Imputing Functional Class

If Generated Functional Class is:	And Rural/Urban Designation is:	Then the Functional Class Code Assigned is:
1 - Interstate	1 (rural)	1 - Principal Art. - Interstate
2 - Other Principal Arterial		2 - Principal Art. - Other
3 - Minor Arterial		6 - Minor Arterial
4 - Major Collector		7 - Major Collector
5 - Minor Collector		8 - Minor Collector
1 - Interstate	2, 3, or 4 (urban)	11 - Principal Art. - Interstate
2 - Other Principal Arterial		12 - Principal Art. - Other Freeways and Expressways
3 - Minor Arterial		14 - Principal Art. - Other
4 - Major Collector		16 - Minor Arterial
5 - Minor Collector		17 - Collector

3.3.1.4 Maximum Traffic Growth Rate

The PreProcessor calculates the traffic growth rate for the section based upon the initial and future AADT values (for details, see paragraph 3.3.3.7).

If the growth rate is greater than the maximum growth rate specified by the user in *MAXGRW*, HERSPP performs the corrective action (one of two) specified by the user in *GRSWITCH*. The user may specify that HERSPP use the growth rate entered in *DEFGRW*. (This is the option in effect when running the HERS-ST GUI, which sets *DEFGRW* to *MAXGRW* before invoking the PreProcessor.)[6] Or the user may instruct HERSPP to display an error message identifying the section and prompt the user to manually enter a growth rate for the section. In either case, HERSPP continues by adjusting the section volume parameters to reflect the new growth rate.

3.3.1.5 Curves and Grades

HERSPP examines the curve and grade classes in each input record to ensure that the total length of reported grades/curves equals the length of the section. HERSPP uses the same validation process for both curves and grades. First, HERSPP totals the lengths of the reported curves/grades. If the reported lengths total less than the section length, HERSPP checks the length reported for the lowest curve/grade class. The lowest class includes those portions of the roadway which have neither curves nor inclines. If the reported length of the lowest class is zero, HERSPP assigns the unreported length to the lowest class. If the reported length of the lowest class is not zero, HERSPP scales the lengths of all the curve/grade classes to total the section length.

If the total reported curve/grade lengths are longer than the section length, HERSPP checks whether the length of any single curve/grade class is greater than the section length. If so, and the sum of the lengths of the remaining classes is less than the sec-

5. The astute reader will note that one of the possible functional classes assigned by HERSPP is Rural Minor Collectors, which is not normally processed by HERS. That this logic was unchanged when Rural Minor Collectors were removed from the HPMS database was an oversight.
6. YO! Should call Tevin/Tom and confirm that this is what it does!

tion length, then HERSPP sets the length of the longest class to the difference between the total length of the other classes and the length of the section. Otherwise, HERSPP scales the lengths of all classes to total the section length.

3.3.1.6 Speed Limit

HERSPP enforces the maximum speed limit specified by the user in the PPSPEC file. It also enforces a minimum speed limit of 15 miles per hour, and sets the limit to the nearest multiple of 5 mile per hour.

3.3.1.7 K and D Factors

If the K-factor is set to zero, HERSPP sets it to 0.1.

HERSPP converts the directional factor entry into a fraction by dividing the integer entry by 100. If the subsequent value is between 0.05 and 0.1 (indicating five and ten percent, respectively) HERSPP assumes an entry error and multiplies the value by ten (setting it between fifty and one hundred percent). Then, if the directional factor is less than fifty percent (0.5), HERSPP sets it to fifty percent and examines the facility type (Item 27). If the section is one-way, it sets the directional factor to 100 percent.[7]

3.3.1.8 Percent Green Time

On sections with traffic signals, HERSPP checks to ensure that a value is entered for percent green time (Item 91). If the entered value is zero, HERSPP issues an informative error message and sets the variable to one of the values specified by the user in *PGTRUR*, as shown in Table 3-10.

Table 3-10. Percent Green Time Default Value Selection

Functional Class	PPSPEC Entry Used
Rural Interstate Rural Principal Arterial - Other Urban Interstate Urban Principal Arterial - Other Freeways or Expressways Urban Principal Arterial - Other	First entry on line 26
Rural Minor Arterial Urban Minor Arterial	Second entry on line 26
Rural Major Collector Urban Collector	Last entry on line 26

HERSPP also enforces the user-specified maximum and minimum percent green time limits entered by the user in the PPSPEC.DAT file.

3.3.1.9 Traffic Control Devices per Mile

The PreProcessor limits the number of traffic control devices (stop signs and traffic signals) per mile to the maximum specified by the user in PPSPEC.DAT (*MAXTCDS*).

3.3.1.10 Turning Lanes

HERSPP examines urban sections with intersections. If the code for either the left or right turn lanes (Items 88 and 89) are zero (rural section or section without intersections), it resets the code to four (turns permitted; no exclusive turning lanes exist).

3.3.1.11 Signalization Validation and Override

HERSPP passes a single value for type of signalization to the HERS-ST analytical engine. HERSPP examines the signalization type override field (*SIGTYPOVERIDE*) and if it is a valid signalization code (that is, from one to four), it copies that value to the output record. If the *SIGTYPOVERIDE* value is not from one to four, HERSPP

7. YO - only checks FT if DFAC < 50%, so HERSPP does not correct for a one0way facility with a DFAC between 50 and 99%. Check w/ Herb for specific reason, or oops.

then validates the *SIGTYP* field: if *SIGTYP* is less than one or greater than three HERSPP sets the field to one.

Note that HERSPP only examines the *SIGTYP* field when the *SIGTYPOVERIDE* field does not specify an override value. Set *SIGTYPOVERIDE* to zero to ensure that the *SIGTYP* field is enabled. Note also that while the validation sequence imposes a default value of one (uncoordinated fixed time) for sections with enabled *SIGTYP* entries of zero (rural sections not reporting signalization) and four (no signal systems exist) as well as for sections with invalid *SIGTYP* entries, the signalization field will not be referenced by the HERS-ST analytical engine for sections without traffic signals.

3.3.2 Default Values

For selected data items, the HERSPP will substitute a default value for missing data.

3.3.2.1 Default Values for Unpaved Sections

HERSPP assigns the following values to all unpaved sections:

- PSR is set to the user-specified value from PPSPEC.DAT;
- SNorD is set to zero;
- Pavement section is set to zero; and
- Accumulated ESALs is set to zero.

3.3.2.2 Other Default Values

For sections with input PSR and IRI of zero, or a PSR value greater than 5.0, HERSPP assigns the default PSR value of 3.2.

HERSPP sets the left shoulder width for all non-divided highways to zero.

HERS requires a positive terrain code (1, 2, or 3) for all sections. The HPMS Field Manual specifies that urban sections be assigned a terrain code of zero. HERSPP changes all terrain code entries of zero to one.

3.3.3 Calculated Values

The PreProcessor calculates a number of values from the input section data. In some cases these values may supply data not included for a particular section. In other cases, the PreProcessor replaces the input data. In most cases the PreProcessor is calculating data needed by HERS but not included in the input data.

3.3.3.1 SN or D

For paved sections without an input value for SN or D (*SNORD*, that is, Structural Number or Depth), HERSPP calculates an initial value based upon annual ESALS. HERSPP first calculates the annual ESALS based upon the reported traffic volume:

$$AESALS = 365 \times AADT \times LANFAC \times (PCAVSU \times EALFAC_{SU} + PCAVCM \times EALFAC_{CM}) \quad \textbf{\textit{Eq. 3.1}}$$

where:

AESALS	=	annual ESALS;
AADT	=	daily traffic (from HPMS input);
LANFAC	=	lane adjustment factor;

PCAVSU	=	percent average single unit trucks (from HPMS input);
PCAVCM	=	percent average combination trucks (from HPMS input); and
EALFAC	=	ESAL adjustment factor, for single unit and combination trucks.

The lane factor adjusts for the number of lanes (in one direction) on the section. The ESAL factor adjusts for the functional class, type of overlay, and truck class. (For a more detailed discussion, see paragraph section 5.1 “The Pavement Deterioration Model” on page 5-1 which presents the ESAL and lane adjustment factors in Table 5-1 and Table 5-2, respectively.)

Next, HERSPP imputes *SNORD* based upon the number of annual ESALS and the type of surface. For high type rigid pavements, HERSPP calculates:

$$SNORD = 5.51 \times AESALS^{0.0383} \qquad \textbf{\textit{Eq. 3.2}}$$

For other pavements, HERSPP calculates:

$$SNORD = 0.979 \times AESALS^{0.1159} \qquad \textbf{\textit{Eq. 3.3}}$$

3.3.3.2 Pavement Section

HERSPP assigns a pavement section (*PAVSEC*) value for each section for use by HERS. The value of *PAVSEC* is based upon the value of *SNORD*, as shown in Table 3-11.

Table 3-11. Assigning *PAVSEC* Values

Rigid Pavement	Flexible Pavement	Pavement Section (*PAVSEC*)
SNORD <= 7	*SNORD* <= 3	5 (Light)
7 < *SNORD* <= 9	3 < *SNORD* <= 4.5	4 (Medium)
9 < *SNORD*	4.5 < *SNORD*	3 (Heavy)

3.3.3.3 ESALs Prior to the Base Year

HERSPP calculates the cumulative number of ESALs on each section at the beginning of the analysis period; that is, the number of ESALs needed to bring about the section’s initial PSR. Sections with PSR of 5.0 or greater are considered new with zero accumulated ESALs. HERSPP begins the calculation by computing the intermediate variables *XA* and *XB*. For flexible pavements, HERSPP uses:

$$SNA = SN + \sqrt{(6/SN)} \qquad \textbf{\textit{Eq. 3.4}}$$

$$XA = 9.36 \times \log(SNA) \angle 0.2 \qquad \textbf{\textit{Eq. 3.5}}$$

$$XB = 0.4 + 1094/SNA^{5.19} \qquad \textbf{\textit{Eq. 3.6}}$$

where *SN* is the structural number.

For rigid pavements, HERSPP uses:

$$XA = 7.35 \times \log(D+1) \angle 0.06 \qquad \textbf{\textit{Eq. 3.7}}$$

$$XB = 1 + 16.24 \times 10^{6}/(D+1)^{8.46} \qquad \textbf{\textit{Eq. 3.8}}$$

where D is pavement thickness.

HERSPP next calculates the variable XG:

$$XG = \log((5 \angle PSRI)/3.5) \qquad \textbf{Eq. 3.9}$$

where *PSRI* is the PSR at the beginning of the base year.

Finally, HERSPP calculates ESALs accumulated on the section prior to the base year:

$$ESAL = 10^{(XA + XG/XB)} \qquad \textbf{Eq. 3.10}$$

3.3.3.4 Time and PSR of Last Pavement Improvement

For unpaved sections, HERSPP designates the original (input) PSR as the PSR after last improvement (*PSR0*), and sets the year of the last pavement improvement (*IMPYR*) negative to indicate that there was no such improvement.

For paved sections, HERSPP uses the year of last surface improvement (Item 53) if supplied, or else the midpoint of the year preceding the base year. PSR after the last improvement is set to the lesser of the initial PSR or the user-specified maximum value of PSR after resurfacing (*PSRRMX*).[8]

3.3.3.5 Weighted Design Speed

HERSPP discards the input weighted design speed (WDS, Item 79) and recalculates it for all sections. The weighted design speed will be used by HERS to determine maximum service flow during capacity calculations on rural and urban multilane sections.

HERSPP follows the procedures outlined in Appendix M of the HPMS Field Manual (December 2000) for estimating weighted design speed on sections with and without reported curve data.[9]

3.3.3.6 Capacity

The PreProcessor calculates the section's base capacity plus peak, off-peak, and counterpeak capacities for the section (see section 4.4.1 "Capacity" on page 4-30 for details). The Preprocessor also sets the section's capacity ratio (*CRATIO*) variable depending upon the value of the input *CALCCAP*.

If *CALCCAP* is set to zero (the default case), the three capacity estimates are calculated from the section's input value for base capacity. (If no capacity was coded for the section, the Preprocessor calculates the base capacity.) The Preprocessor then sets *CRATIO* to the coded capacity divided by the calculated base capacity. This identifies sections whose conditions result in capacity different from that calculated by the HCM procedures. HERS assumes that the factors which determine the capacity difference are not reflected in the section's geometric data items, and captures the ratio of the difference in *CRATIO*. When recalculating the section's capacity after improvement, HERS further assumes that the unknown factors affecting capacity are still in effect, and uses *CRATIO* to maintain the ratio between the effective and calculated section capacities.

8. Nonetheless, HERS v. 3.5.4 subsequently references neither of these parameters.
9. The sole variation is on non-multilane sections without curve data. For these, HERSPP calculates weighted design speed as if the section were multilane. This is acceptable because HERS will only use weighted design speed if it considers adding lanes to the section, in which case it will become a multilane section.

If *CALCCAP* is set to one, HERS uses the calculated base capacity as the basis for estimating the trio of peak capacities. It then replaces the coded base capacity with the calculated capacity and sets *CRATIO* to one.

HERSPP also checks to ensure that the ratio of daily volume to capacity (*AADT*/ Capacity) is less than the maximum ratio specified in *MAXR*. If it is greater than the specified maximum, HERSPP increases the section's capacity until it meets the *MAXR* limit. HERSPP then sets *CRATIO* using the increased capacity.

3.3.3.7 Traffic Growth Rates

HERSPP uses the initial and forecast traffic volumes from the input record to compute growth rates for the section.

HERS provides the user with the flexibility to project baseline traffic using one of several options, each reflecting different travel growth characteristics. Parameters for each option are initialized by the PreProcessor, and are determined so that, were no elasticity applied, traffic volume on the section would reach the specified Future AADT value at the Future AADT Year. Option One is for concave geometric growth, Option Two is for linear growth, and Option Three provides for convex geometric growth, as shown in Figure 3-1.

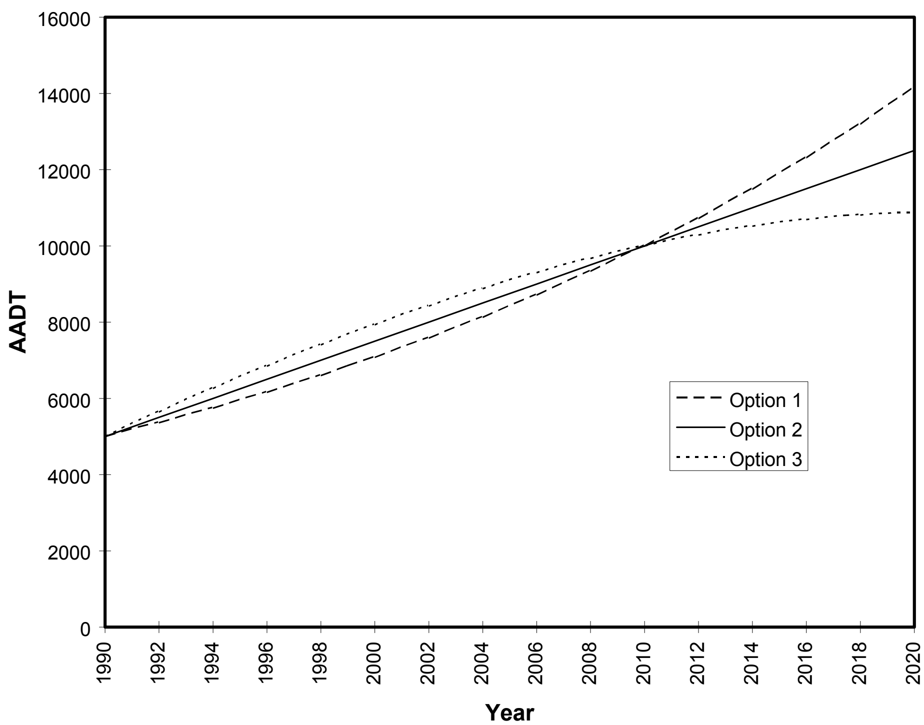

Figure 3-1. Travel Growth Options

The example in Figure 3-1 is of a section with an initial AADT of 5000 in data year 1990. The future AADT year is 2010, at which time the AADT will have grown to 10,000. The growth rate is calculated for each section based upon the data in its HPMS record. The trend lines show baseline traffic volume without the application of demand elasticity. The linear growth method (option Two) was used for the 1997, 1999, and 2002 editions of the *C&P Report*.

3.3.3.7.1 Option One - Concave Geometric Growth

The geometric option projects baseline traffic by applying a constant rate of growth throughout the analysis period. Because the volume of additional traffic each year is based upon the previous year's volume, more vehicles are added each year. The Pre-Processor calculates the growth factor, AADTGR:

$$AADTGR = \left(\frac{FAADT}{AADT}\right)^{1/(FAADTYR \angle AADTYR)} \qquad \textbf{\textit{Eq. 3.11}}$$

where:

AADTGR	=	constant growth rate;
FAADT	=	Future AADT from HPMS section record;
AADT	=	current AADT from HPMS section record;
FAADTYR	=	year of Future AADT from HPMS section record; and
AADTYR	=	year of current AADT from HPMS section record.

AADT for any time t_1 may be projected along a concave curve:

$$AADT_{t_1} = AADT_{t_0} \times AADTGR^{(t_1 \angle t_0)} \qquad \textbf{\textit{Eq. 3.12}}$$

where:

$AADT_{t0}$	=	known AADT at time t_0.

3.3.3.7.2 Option Two - Linear Growth

The second option applies a linear, or constant, growth function throughout the period, so that the same number of vehicles are added each year. The growth factor (*AAGRSL*) is calculated by the PreProcessor:

$$AAGRSL = \frac{FAADT \angle AADT}{FAADTYR \angle AADTYR} \qquad \textbf{\textit{Eq. 3.13}}$$

where:

AAGRSL	=	straight line growth rate.

Using the linear growth function, AADT is projected:

$$AADT_{t_1} = AADT_{t_0} + AAGRSL \times (t_1 \angle t_0) \qquad \textbf{\textit{Eq. 3.14}}$$

This is the growth option used for the 1997, 1999, and 2002 versions of the *C&P Report*.

3.3.3.7.3 Option Three - Convex Geometric Growth

In the third option, the geometric and linear models are combined to project growth along a convex curve. This curve is the mirror image of the concave geometric curve relative to the linear growth function, and provides for rapid initial growth followed by less aggressive growth. Future AADT at time of interest t_1 is calculated:

$$AADT_{t_1} = 2 \times (AADT_{t_0} + AAGRSL \times (t_1 \angle t_0)) \angle AADT_{t_0} \times AADTGR^{(t_1 \angle t_0)} \qquad \textbf{\textit{Eq. 3.15}}$$

3.3.3.7.4 Additional Growth Rate Considerations

If the input future volume *FAADT* is zero, HERSPP sets *FAADT* to the initial volume (*AADT*) and assumes a zero growth rate. If the future year *FADTYR* is input as zero, HERSPP sets it to the data year (*AADTYR*) plus 20.

If the concave geometric growth rate *AADTGR* is greater than the maximum growth rate *MAXGRW*, HERSPP sets *AADTGR* to *MAXGRW*. It then sets *FADTYR* to *AADTYR* plus 20 and calculates a new value for *FAADT* using *MAXGRW*. HERSPP then re-calculates *AAGRSL* using the revised *FAADT*. (See paragraph 3.3.1.4 for further details.)

3.3.3.8 Geometric Values

HERSPP calculates four values for each section for later use by the HERS rural two-lane crash procedure: average curvature, average grade, and curve and grade factors.

HERSPP uses the following algorithm to compute both the average degree of curvature and the average grade of each section:

$$AVG = \frac{\left(\sum_{c=1} LEN_c \times TYP_c\right)}{SLEN} \qquad \textbf{\textit{Eq. 3.16}}$$

where:

AVG	=	Average degrees of curvature or average grade;
LEN_c	=	Length of section within each curve/grade class "c";
TYP_c	=	"Typical" curvature or grade for each curve/grade class "c" (see Tables 3-12 and 3-13);
SLEN	=	Section length;

and the summation includes all six curve/grade classes.

To compute the curve factor, HERSPP employs the following algorithm:

$$CFAC = \sum_{c=1}^{\text{ʊ}} \frac{LEN_c}{SLEN \times \exp(0.045 \times TYP_c)} \qquad \textbf{\textit{Eq. 3.17}}$$

where *CFAC* is the curve factor, and the other terms are as in Equation 3.16.

Similarly, HERSPP computes the grade factor:

$$GFAC = \sum_{c=1}^{\text{ʊ}} \frac{LEN_c}{SLEN \times \exp(0.11 \times TYP_c)} \qquad \textbf{\textit{Eq. 3.18}}$$

where *GFAC* is the grade factor, and the other terms are as in Equation 3.16.

Table 3-12. Curve Class Associated Values

Curve Class	Minimum Degree of Curvature	Maximum Degree of Curvature	"Typical" Values Used in Equation 3.16	Design Speed
A	0.0	3.4	0.4	70
B	3.5	5.4	4.6	60
C	5.5	8.4	6.3	50
D	8.5	13.9	11.8	40
E	14.0	27.9	18.9	30
F	28.0	--	33.0	25

Table 3-13. Grade Classes

Grade Class	Minimum Gradient (Percent)	Maximum Gradient (Percent)	"Typical" Values Used in Equation 3.16
A	0.0	0.4	0.2
B	0.5	2.4	1.45
C	2.5	4.4	3.45
D	4.5	6.4	5.45
E	6.5	8.4	7.45
F	8.5	--	10.0

3.3.3.9 Horizontal and Vertical Alignment Adequacy

HERSPP can calculate the vertical and horizontal adequacy for certain sections. These sections are:

- Rural sections with curves or grades reported, and
- Urban principal arterials with curve data reported.

The user indicates, via *AASWITCH* in control file PPSPEC.DAT, whether the values for alignment adequacy coded in the section input record should be used whenever they are supplied, or if HERSPP should recalculate the adequacy values when the curve/grade information is reported.

HERS uses the procedure from the HPMS submittal software.[10]

3.3.3.10 Peak Percent Trucks

HERSPP sums the peak percent single unit trucks (*PCPKSU*, Item 81) and peak percent combination trucks (*PCPKCM*, Item 83) to derive the percentage of total truck travel during the peak period.

3.3.3.11 Urban Freeways

HERSPP determines whether each urban section is an "urban freeway by design" and/or a "substandard urban freeway." (An urban section could be either, both, or neither.) The designations are for later use by HERS in evaluating the section. To be considered an urban freeway by design, a section must meet the following criteria:

10. YO And I'd prefer to refer the reader there, rather than include an exhaustive review of the 300+ line procedure here.

- the section must be urban;
- it must have at least four through lanes;
- it must have either full or partial access control; and
- the median must be either a positive barrier or have a width of at least four feet.

To be designated a substandard urban freeway, a section must be in functional class 11 (urban interstate) or 12 (urban other freeways and expressways) and at least one of the following conditions must apply:

- the shoulders are not surfaced;
- access is not fully controlled;
- median type is not positive barrier; or
- median width is less than the design standard.

3.3.3.12 Geometrics Following Alignment Improvement

For certain sections, HERSPP calculates new values for parameters which would be affected by an alignment improvement on the section. Eligible sections are rural sections and urban principal arterials, where either or both curves or grades are reported. On sections where curve data is coded, the affected parameters are:

- length of corrected curves after re-alignment (*LAFTH*);
- average degrees of curvature; and
- curve factor for safety calculations (see Equation 3.17).

On sections where grade data is included, the affected parameters are:

- length of corrected grades after re-alignment (*LAFTV*);
- average gradient; and
- grade factor for safety calculations (see Equation 3.18).

The PreProcessor also recalculates the section's weighted design speed after alignment improvement.

3.3.3.13 Wet

The PreProcessor examines the General Climate Zone input (item number 52) and sets the *WET* variable accordingly. The variable is set to one for the three wet climate codes (zones one through three), or to zero for the intermediate or dry codes.

3.3.3.14 Parameters for Delay Calculations

HERSPP sets up several parameters for later use in the calculation of delay due to congestion and traffic control devices. These parameters include:

- the section's classification into one of six delay categories (see Table 5-15);
- a flag indicating whether the section contains both stop signs and traffic signals;

and for sections with either or both traffic signals and stop signs:

- the average number of traffic control devices per mile;
- the average distance between traffic control devices;

- the ratio of stop signs to all traffic control devices; and
- the ratio of traffic signals to all traffic control devices.

3.3.4 Conversions

HERS accepts some data items in a form or format that is different from what the model uses internally, and these items are converted by the HERSPP.

3.3.4.1 Percentage Conversions

Several of the section input fields are entered as integers representing percent, that is, "70" is entered meaning 70 percent. HERSPP divides these fields by 100, expressing the percent as a fraction of one. This transforms the 70 percent example to an internal representation of 0.70. HERSPP performs this conversion for the following fields:

- Peak percent single unit trucks - *PKPCTTRKSU* (Item 81)
- Average daily percent single unit trucks - *PCAVSU* (Item 82)
- Peak percent combination trucks - *PKPCTTRKCM* (Item 83)
- Average daily percent combination trucks - *PCAVCM* (Item 84)
- K-factor - *KFAC* (Item 85)
- Directional factor - *DFAC* (Item 86)
- Typical peak percent green time - *PCTGRN* (Item 91)

3.3.4.2 County Code Conversion

When the section's state code indicates that the section is in Alaska, the section's county code is multiplied by 10.

3.3.4.3 Shoulder Type Code Conversion.

HERS and the HPMS use differing codes to describe shoulder types: the HPMS recognizes six shoulder types, while HERS only processes four. HERSPP converts the HPMS codes into internal HERS codes as shown in Table 3-14.

Table 3-14. HERS Shoulder Condition Codes

HPMS Code	HERS Code	Description
1	3	None: no shoulders or curbs exist.
2	1	Surfaced shoulder (bituminous concrete or Portland cement concrete surface).
3	1	Stabilized shoulder (stabilized gravel or other granular material with or without admixture).
4	2	Combination shoulder (shoulder width has two or more surface types; for instance, part is surfaced and part is earth).
5	3	Earthen shoulder.
6	4	Barrier curb exists; no shoulders in front of curb.

3.3.4.4 Surface Type Code Conversion

HERS and the HPMS also use differing codes to describe a section's surface. While the HERS codes identify five of the six surfaces coded in the HPMS record, HERS sets the logical variable *COMPOS* to true to indicate when a section with a high flexible surface type consists of a flexible overlay on a previously existing rigid surface. HERSPP converts the Surface/Pavement Type codes as shown in Table 3-15.

Table 3-15. HERS Surface Type Codes

HPMS Code	HERS Code	Description
1	5	Unpaved.
2	4	Low type.
3	3	Intermediate type.
4	1	High type flexible.
5	2	High type rigid.
6	1 (*COMPOS* flag set to true)	High type composite.

3.3.4.5 Metric to English Conversion

Internally, the HERS model utilizes English units of measure. Conversion from metric to English units is performed by the PreProcessor and is conditioned upon each section's UNITS field. Table 3-16 lists the conversions performed by HERSPP.

Table 3-16. Metric Conversions

Metric Unit	English Unit	Conversion	Fields	
			Item	Description
kilometer	mile	mile = km / 1.609344	30	Section length
			63 - 68	Curve class lengths
			72 - 77	Grade class lengths
			79	Weighted design speed
			80	Speed limit
Meter (xx.x)	Foot	feet = meter / 0.3048	57	Median width
			59	Right Shoulder Width
			60	Left Shoulder Width
Millimeters	Inches	inches = millimeters / 25.4	51	SN or D
Meters per Kilometer	Inches per Mile	inches = meters * 63.36	35	IRI

There are three special cases in which HERSPP uses a "hard" conversion. The first case applies to speed limit and weighted design speed. When the input speed (in kilometers-per-hour) is a multiple of 5 between 10 and 120, HERSPP looks up the corresponding miles-per-hour speed as shown in Table 3-17. If the input speed is less than 10 or more than 120 kph, or is not a multiple of 5, HERSPP performs the conversion shown in Table 3-16.

In the second special case, HERSPP uses the hard conversion of meters to feet shown in Table 3-18 for shoulder widths through 3.8 meters; for wider widths, it uses the conversion in Table 3-16.

Finally, HERSPP uses the hard conversion values shown in Table 3-19 to convert lane widths from meters to feet. The minimum lane width is six feet, and the maximum allowed lane width is eighteen feet.

Table 3-17. Hard Conversion for Speed: Kph to Mph

Kilometers per hour	Miles per hour	Kilometers per hour	Miles per hour	Kilometers per hour	Miles per hour
10	5	50	30	90	55
15	10	55	35	95	60
20	10	60	35	100	60
25	15	65	40	105	65
30	20	70	45	110	70
35	20	75	45	115	70
40	25	80	50	120	75
45	30	85	55		

Table 3-18. Hard Conversion for Shoulder Width: Meters to Feet

Meters	Feet	Meters	Feet	Meters	Feet
0.1	1	1.4	5	2.7	9
0.2	1	1.5	5	2.8	9
0.3	1	1.6	5	2.9	10
0.4	1	1.7	6	3.0	10
0.5	2	1.8	6	3.1	10
0.6	2	1.9	6	3.2	10
0.7	2	2.0	7	3.3	11
0.8	3	2.1	7	3.4	11
0.9	3	2.2	7	3.5	11
1.0	3	2.3	8	3.6	12
1.1	4	2.4	8	3.7	12
1.2	4	2.5	8	3.8	12
1.3	4	2.6	9		

Table 3-19. Hard Conversion for Lane Width: Meters to Feet

Meters	Feet	Meters	Feet	Meters	Feet
less than 1.7		3.0	10	4.4	14
1.7		3.1	10	4.5	15
1.8		3.2	10	4.6	15
1.9	6	3.3	11	4.6	15
2.0		3.4	11	4.8	16
2.1		3.5	11	4.9	16
2.2	7	3.6	12	5.0	16
2.3	8	3.7	12	5.1	17
2.4	8	3.8	12	5.2	17
2.5	8	3.9	13	5.3	17
2.6	9	4.0	13	5.4	18
2.7	9	4.1	13	5.5	18
2.8	9	4.2	14	5.6	18
2.9	10	4.3	14	5.7 or greater	18

3.3.4.6 IRI to PSR Conversion

HERS' internal calculations use PSR to represent pavement condition when evaluating deficiencies, determining speed, calculating vehicle operating costs, estimating agency maintenance costs, and forecasting pavement deterioration.

Table 3-20 presents descriptions of pavement characteristics corresponding to the various PSR levels. The exhibit also displays the IRI values (for rigid pavement) for the integer PSR values from one through five. The lowest value shown for PSR (0.068) was chosen to correspond to an IRI of 999.

Section input records might contain either, both, or neither PSR or IRI values. The HERSPP control file, PPSPEC.DAT, contains a flag to give the user control over selecting PSR or IRI for sections which contain both entries. Table 3-21 displays the logic used by HERSPP in determining the source of the PSR value which is passed to the HERS program. HERSPP selects one of three equations for the IRI to PSR conversion based upon the section's surface type. Table 3-22 displays the three equations.

3.3.5 Processing the User-Specified Improvements File

HERSPP reads the PPSPEC.DAT text file for the following three items which control the processing of user-specified improvements:

- the Override Flag;
- the name of the text file containing the user-specified improvement information; and

Table 3-20. Pavement Condition Ratings[a]

PSR and Verbal Rating	IRI Value (Rigid)[b]	Description
5.0	**0**	
Very Good		Only new (or nearly new) pavements are likely to be smooth enough and sufficiently free of cracks and patches to qualify for this category. All pavements constructed or resurfaced during the data year would normally be rated very good.
4.0	**52**	---
Good		Pavements in this category; although not quite as smooth as those described above, give a first class ride and exhibit few, if any visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalling.
3.0	**119**	---
Fair		The riding qualities of pavements in this category are noticeably inferior to those of new pavements and may be barely tolerable for high speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and cracking, and some pumping.
2.0	**213**	---
Poor		Pavements that have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes ravelling, cracking, rutting, and occurs over 50 percent or more of the surface. Rigid pavement distress includes joint spalling, faulting, patching, cracking, scaling, and may include pumping and faulting.
1.0	**374**	---
Very Poor		Pavements that are in an extremely deteriorated condition. The facility is passable only at reduced speeds and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.
0.068	**999**	

a. Source: U.S. Department of Transportation, Federal Highway Administration, *Highway Performance Monitoring System Field Manual*, Washington, D.C., December 1987, p.IV-28. The version in the April 1994 edition excludes the verbal ratings.

b. Rounded to whole inches per mile.

- the name of the binary file to contain the processed user-specified improvement information.

If the Override Flag is set to zero, HERSPP deletes any existing copy of the specified binary file. Otherwise, HERSPP processes the text file and creates a new copy of the binary file.

Table 3-21. Derivation of Initial PSR Value

Input record Contains	User Flag Specifies	Source of Initial PSR
Both PSR and IRI	PSR	Input PSR
Both PSR and IRI	IRI	HERSPP converts input IRI to PSR
PSR only	n/a	Input PSR
IRI only	n/a	HERSPP converts input IRI to PSR
Paved section, neither PSR nor IRI reported	n/a	Default PSR value of 3.2
Unpaved section	n/a	User-specified default PSR for unpaved sections

Table 3-22. IRI to PSR Conversion Equations

Surface Type	Equation
Flexible	$PSR = 5.0 \times \exp(\angle 0.0038 \times IRI)$
Composite	$PSR = 5.0 \times \exp(\angle 0.0046 \times IRI)$
Rigid	$PSR = 5.0 \times \exp(\angle 0.0043 \times IRI)$

HERSPP first validates that the number of improvements specified (EI_COUNT) is within range. If not, it sets the flag VALID to false.

HERSPP then checks for invalid conditions when setting the override code to zero or the improvement year to zero, as shown in Table 3-23.

Table 3-23. Error Conditions for User-Specified Improvement Input

Year	Improvement Type	OverRide	
non-zero	0	0	err msg: bad prevent, discard imp
0			discard improvement
	0	0	discard improvement

HERSPP examines the user-specified improvement code. If the code indicates adding lanes, it checks the *EI_LANES* code. If it is equal to zero, it sets *EI_LANES* to 1 and issues a warning message.

If the sum of existing lanes and added lanes is odd, and the section is two-way, and the user has not specified the new capacity, HERSPP makes the final number of lanes even. (This is because the capacity routines do not have the capability to figure capacity for odd-laned two-way facilities.) If the number of lanes being added is odd, the number is increased by one; if even, it is decreased by one. HERSPP issues a warning message.

If the improvement does not add lanes, then HERSPP sets the number of lanes being added to zero and issues a warning msg. (The improvement type overrides the number of lanes entry.)

If the user has specified a combination improvement (HERS type + non-HERS type), HERSPP checks the override flag. If it is not set to one, HERSPP forces it to one and issues a warning message.

The model next has code to handle the case of an override code equal to zero and an improvement type set to zero, in which it would set the override code to one. This code assumes that the user wanted to specify that the section would be unimproved during the funding period. However, previous code would have discarded this improvement. This code is therefore never exercised. <<YO-- need to ask David/ Herb/Nate.

If the specified improvement is a pure non-HERS type (that is, not in combination w/ a HERS type imp) and the user has not specified a cost for the imp, HERSPP assigns a cost of $1.00.

If the improvement is a combination of HERS-type and non-HERS-type, and no cost has been specified, HERSPP sets the cost to $2.00. The code is annotated: HERS will later recognize the $2 as a special value indicating it should use the cost of the HERS-type improvement as the total cost of the improvement.

HERSPP next sets EI_YEAR(J) to the year, relative to the baseyear (which is now read per record, rather than from the distribution file), in which the improvement is to be implemented. The algorithm, although noting a possible 2070 problem, actually doesn't work for base years before 1970.

HERSPP finally writes the binary output record for the section. Table 3-24 displays the output record format. As with the input record, the first three fields identify the section, and the remaining fields define improvements. Unlike the input format, where the minimum number of fields are used to define the desired improvements, the binary record contains a set of arrays. The arrays provide sufficient elements for the maximum number of definable improvements. HERSPP does not indicate the meaning of the Used flag, and the final scalar flag is not named.

Table 3-24. User-Specified Improvement Output File Fields

Field		Item		Format
1.	Number of Improve-ments	scalar		integer
2.	County Code	scalar		integer
3.	Sample Identifier	scalar		alphanumeric
4.	Year of Improvement	array		integer
5.	Relative Year of Improvement	array		integer
6.	Type of Improvement	array		integer
7.	Type of HERS improve-ment	array	1-19	integer
8.	Type of Non-HERS Improvement	array	0,20,40,60, or 80	integer
9.	Override Flag	array		integer
10.	Cost of Improvement	array		floating point
11.	Lanes To Add	array		integer
12.	Increase in Capacity	array		integer
13.	“Used” Flag	array	.false	logical
14.	Another Flag	scalar	.false	logical

Chapter 4:

Design of Improvement Alternatives

The highway improvements analyzed by HERS consist of various combinations of pavement, widening and alignment improvements. The user has the option of specifying improvements for each section by using the "override" mode. Otherwise, HERS assesses each section for deficiencies, and then designs improvements to correct these deficiencies.

This chapter begins with a discussion of user-specified improvements and the override mode. The second part of this chapter discusses the improvements that HERS designs, including: the section characteristics and types of deficiency levels that HERS utilizes in determining whether potential improvements should be evaluated; a definition of the HERS improvement types and the procedures used in designing them; and the effects of the HERS improvements upon section characteristics. The chapter closes with discussions of two aspects of adding or widening lanes: the application of the widening feasibility parameters, and the use of the capacity model to determine how many lanes are needed in the design year.

4.1 The Override Mode and User-Specified Improvements

In override runs, the HERS-ST user has the ability to override some (or all) of the decisions HERS makes regarding the selection of improvements, the initial cost of these improvements, and their effects on capacity. In particular, for any section, the user can specify:

- That a particular type of improvement is to be made in a particular FP;
- The initial cost of such an improvement;
- Its effect on capacity; or
- That improvements are to be made only in specified FPs.

Override runs make it possible to override HERS-ST decisions on the basis of specific knowledge of the feasibility of particular improvements selected by HERS-ST or knowledge of unusual costs (e.g., for replacing bridges) that would be incurred in implementing these projects. These runs also make it possible to require that several related improvements (such as widening a given highway) be scheduled for the same FP or in consecutive FPs (because HERS analyzes individual sections in isolation, it is not currently capable of recognizing the relationship between such improvements).

Override runs also make it possible for HERS-ST users to specify improvements not selected by HERS. These improvements can be either HERS-type improvements (pavement, widening, or alignment improvements) or other types of projects (such as intersection modification or grade separation). In the latter case, the user must specify both the initial cost of the project and its effect on capacity. For HERS-type improvements, the user has the choice of providing cost and/or capacity specifications or allowing HERS to estimate these quantities.

Section 4.1.1 describes how users can specify improvements that should or should not be made and, optionally, specify the initial costs of these improvements and/or their effects on capacity. Section 4.1.2 describes some of the output describing the effects of such user-specified improvements. Finally, Section 4.1.3 provides details about how HERS-ST estimates the costs and benefits of user-specified improvements as well as the incremental costs and incremental benefits of substituting a more aggressive improvement for a user-specified improvement.

4.1.1 User-Specified Improvements

For a given section, user-specified improvements are described in an optional “State Improvements,” or “StateImp” file. The name of this file is entered on the File Specifications screen of the HERS GUI Control Model or as the *STATEIN* input in PPSPEC.DAT. The HERS preprocessor reads this file and writes a binary version that is passed to the main HERS program.[1]

Each record of the StateImp file describes one or more improvements for a single highway section in chronological order. This information can be entered using the State Improvements data window of the HERS GUI, or it can be entered directly into the StateImp file using a comma-delimited format. Each record of the file contains 6*n*+3 fields, where *n* is the number of improvements described. The contents of the first 10 fields of this file are shown in Table 4-1.

Table 4-1. Record Format of State Improvements File

Field	Format
1. Number of improvements	Integer
2. County Code	Integer
3. Sample Identifier	Alphanumeric
4. Year of First Improvement (four digits)	Integer
5. Type of improvement	Integer
6. Override Flag	Integer
7. Cost of Improvement	Decimal
8. Lanes Added	Integer
9. Increase in Capacity	Integer
10. Year of Second Improvement	Integer
Continue for up to 10 improvements	

1. The GUI handles the passing of the binary file automatically. If the GUI is not being used, enter the name of the file to be created as the *STATEOUT* input of PPSPEC.DAT and the *STATEIMPS* input of RUNSPEC.DAT.

The first field of each record specifies the number of improvements described. A maximum of 10 improvements can be described in any record.

The next two fields contain the county code and the Sample Identifier (from HPMS Field 47). These fields are used to match the StateImps record with the corresponding HPMS record describing the section in question.[2]

User-specified improvements are entered in chronological order in sets of six fields (Fields 4 - 9, 10 - 15, etc.).

For the first improvement, a particular type of improvement is specified for a particular FP by setting the year (Field 4) to any year in that FP and identifying the improvement type in Field 5. For HERS-type improvements, the improvement type is specified using the codes in Table 8-3.[3] Other types of improvements (such as intersection modification or grade separation) should be assigned codes that are divisible by 20 when they are not combined with pavement, widening, or alignment improvements. The combination of a non-HERS-type improvement with pavement, widening, and/or alignment improvements should be assigned a code that is the sum of a code that is divisible by 20 and the appropriate code from Table 8-3.[4] Improvements that are not HERS-type or are combinations of HERS-type and non-HERS-type are called *special improvements* by HERS-ST.

If the first improvement involves adding lanes, the number of lanes to be added is specified in Field 8. An entry in this field is required for improvement types that end in 4, 5, 8, or 9; and this field only has an effect for improvement types that end in 4, 5, 8, or 9 (i.e., the lanes specified in Field 8 are added only if an “add lanes” improvement is specified). On two-way roads, HERS-ST normally assumes that, after the addition of lanes, the number of travel lanes will be even, and the current system does not have procedures for estimating capacity if the number of travel lanes will be odd. Accordingly, if the resulting number of lanes will be odd, the increase in capacity must be specified by the user in the last of the fields describing the improvement (Field 9 for the first improvement). Otherwise, a message is printed and the number of added lanes is adjusted appropriately (if an odd number of added lanes is specified, the number is increased by one; otherwise, the number of added lanes is reduced by one). If lanes are to be added but the lanes-added field is zero, HERS-ST adds either one lane (on one-way facilities) or the minimum number of additional lanes that will produce an even number of lanes (on two-way facilities), and a message to this effect is printed.

The initial costs of a user-specified improvement may be provided (in thousands of dollars), and the change in peak-hour capacity may be provided (in passenger-car equivalents per hour). For the first user-specified improvement, Fields 7 and 9 are used. For rural two- and three-lane roads, capacity changes should be specified as

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2. The match will be unique if all HPMS records are from a single state. If data from multiple states are used in a single run, there is a small probability that the same County/Sample-ID pair will be used to identify sections in more than one state. In this case HERS-ST 2.0 will arbitrarily match the StateImps record to the first HPMS record that it finds.
3. For unpaved sections, all improvements should entail pavement reconstruction. HERS treats user-specified improvements that do not entail pavement reconstruction as entailing reconstruction and prints a warning.
4. For example, the user might use an improvement type of 20 (or 40) to represent construction of an overpass. The construction of an overpass combined with resurfacing the entire section would then be represented by Type 21 (or 41).

changes in two-way capacity; for all other roads they should be specified as changes in peak-period, peak-direction capacity. For HERS-type improvements, if these fields are blank or zero, the HERS-ST estimates of improvement costs and/or new capacity will be used. For all special improvements, these fields must contain non-zero values.

The override flag (Field 6 for the first user-specified improvement) is used to indicate whether HERS-ST has any leeway in modifying a user-specified improvement. For HERS-type improvements (Types < 20) and pure non-HERS-type improvements (Types divisible by 20), this flag may be set to either zero or one. For improvements that are combinations of HERS-type and non-HERS-type improvements (Type greater than 20 and not divisible by 20), this flag must be set to one.

If the override flag is set to one, the project is selected just as described in the set of six fields. If it is set to zero, these fields describe the *minimum* improvement that will be selected. In this case, HERS-ST may identify a "more aggressive" improvement that warrants evaluation; i.e., an improvement that incorporates more widening than requested and/or also improves the section's alignment. If any more aggressive improvements are identified, the incremental benefits and costs of these improvements are estimated and used for determining whether any of the additional options should be implemented.

In addition to controlling whether HERS-ST can modify a user-specified improvement, the override flag controls the insertion by HERS-ST of improvements prior to the implementation of a user-specified improvement. If the override flag for the next user-specified improvement is one, HERS-ST does not consider any improvements until after the corresponding FP. On the other hand, if it is zero, HERS-ST considers the possibility that a pavement or widening improvement may be warranted in an earlier FP and, if so, an appropriate improvement is selected for the earlier period. In this case, if the user-specified improvement is of Type 1, 2, or 6 (i.e., the kind of improvement that can be analyzed by a Pavement Management System), the two improvements are combined and assigned to the earlier FP (but only if the user-specified improvement would otherwise be implemented prior to the end of the last FP to be analyzed during the run). When two improvements are combined in this way, any subsequent user-specified improvements with override flags of zero are advanced appropriately. If the user-specified improvement is not of Type 1, 2, or 6, its timing is not adjusted, but HERS-ST prints a message to alert the user to the possibility that the number of improvements selected for the section may be more than are warranted.

As implied in the preceding paragraph, the override flag can be used to prevent HERS-ST from selecting improvements for a section in one or more FPs. For this purpose, a set of six user-specified improvement fields is used with an appropriate year in the year field, an improvement code of zero, and an override flag of one. If these fields represent the first user-specified "improvement" to be implemented (i.e., if they are Fields 4 - 9), no improvements will be considered by HERS-ST until *after* the FP corresponding to the coded year. If there are one or more earlier user-specified improvements coded, the period when no improvements are considered starts after the last of the user-specified improvements. For example, if the first user-specified improvement is requested for FP 1, the second set of improvement fields can be used in this way to specify that no subsequent improvements be considered until FP 4 (by setting the year in the second set of improvement fields to a year that falls in FP 3). Similarly, if the *first* set of improvement fields contains an improvement code of zero, an override flag of one, and the same year (in FP 3) in the year field, *no* improvement will be considered until FP 4.

In each FP, HERS-ST automatically selects all user-specified improvements for implementation regardless of their benefit/cost ratios (BCR). If a funding constraint is in effect, the cost of these improvements is subtracted from the budget for the FP before any consideration is given to selecting other improvements or choosing to go beyond the user-specified minimum improvement for any section for which such an improvement is specified. If the cost of implementing all user-specified improvements exceeds the funding constraint for the FP, a message is printed and the funding constraint for the next FP is reduced accordingly. Similarly, if a performance goal is in effect, the benefits of user-specified improvements are taken into account before considering any improvements or improvement options that are not user specified.

4.1.2 Evaluations of Individual Improvements

Descriptions and evaluations of all improvements selected for a particular FP are contained in the section file (SECNSnn.OUT) produced for that FP. The contents of this file are described in section 8.3 "Section Output Files" on page 8-11. For any section, comparisons of the benefits and costs of alternative improvements can be obtained by specifying each alternative in a separate override run and comparing the resulting evaluations in the improvement files that are produced.

4.1.3 Benefits and Costs

This section provides details of how HERS-ST estimates the user benefits and improvement costs of user-specified improvements and also the corresponding incremental benefits and incremental costs of replacing a user-specified improvement by a more aggressive improvement.

4.1.3.1 Improvement Costs

If the cost of any user-specified improvement is specified, HERS-ST uses that cost as the cost of the improvement. Otherwise, if the improvement is a HERS-type improvement, HERS-ST estimates the cost using the HERS procedure for estimating improvement costs (as described in Chapter 6, "Capital Cost of Improvements."). If no cost is provided for a special improvement, HERS-ST prints a warning message and sets the improvement cost to a default value.[5]

When evaluating the possibility of replacing a HERS-type user-specified improvement (e.g., resurfacing, as identified by a State's Pavement Management System) by a more aggressive improvement (e.g., resurface and add lanes), HERS estimates the *incremental* cost of replacing the former improvement by the latter one. This incremental cost is estimated as the difference between estimates of the costs of the two improvements that are *both* obtained using HERS' procedure for estimating improvement costs (regardless of whether the user has provided an exogenous cost estimate for the user-specified improvement).

Consider the possibility of replacing a non-HERS-type user-specified improvement (Type divisible by 20) by a combination of that improvement and a HERS-type of improvement. The cost of the combined improvement is estimated by using the HERS procedure for estimating improvement costs to estimate the cost of the HERS-type of improvement, and adding this cost to the cost of the original user-specified

5. When the special improvement combines a non-HERS-type improvement with a HERS-type improvement, the default cost is the cost of the HERS-type improvement. Otherwise, it is one dollar per section.

improvement. Thus, the resulting estimate of the incremental cost of adding the HERS-type improvement ignores any efficiencies obtained by implementing both improvements simultaneously; and so there may be a tendency to overestimate the incremental cost. If the first improvement applies only to an intersection or interchange and the second applies to an entire section, this effect is likely to be fairly small[6] and so may be ignored. If both improvements apply to the entire section, however, the effect may be more significant. For this reason, HERS-ST will tend to overestimate the incremental cost of adding a HERS-type improvement to a user-specified improvement that affects an entire section. Also for this reason, HERS-ST requires that the override flag be set to one for user-specified improvements that combine HERS-type and non-HERS-type improvements.

4.1.3.2 User Benefits

HERS-ST estimates the user benefits of an improvement as the net reduction in user costs resulting from changes in the physical characteristics of the improved section (including increases in the number of lanes) and from the resulting increases in capacity and average speed.

In the case of user-specified improvements, any increase in the number of lanes *must* be specified by the user and any increase in capacity *may* be specified. The user benefits of a non-HERS-type improvement (Type divisible by 20) are estimated entirely from these two increases. For such improvements, if both fields are zero, estimated benefits will be zero (if only the second field is zero, however, increased capacity will be estimated from the increase in the number of lanes.)

User-specified improvements that either are purely HERS-type (Type < 20) or are a combination of HERS-type and non-HERS-type (Type not divisible by 20), may produce other changes in the physical characteristics of the section. These are simulated by HERS-ST, and thus they provide another potential source of information for estimating user benefits. For these sections, the estimates of user benefits reflect any non-capacity effects of these changes plus either the user-coded change in capacity or, if the capacity change is not coded, the HERS-ST estimate of change in capacity.

When evaluating the possibility of replacing a user-specified improvement by a more aggressive improvement, HERS-ST estimates the *incremental* user benefits of the replacement by analyzing the effects of the replacement on the physical characteristics of the section and the resulting effects on user benefits. This process is straightforward when the user does *not* specify the capacity effects of the user-specified improvement, but it requires some clarification for the case in which the user does specify these effects. In the latter case, we distinguish several different estimates of capacity:

1. Estimated capacity before implementation of the user-specified improvement;
2. Estimated capacity after implementation of this improvement – obtained by adding the user-coded capacity effect of the improvement to (1);
3. A separate estimate of capacity after implementation of the improvement that is produced by HERS-ST entirely from the physical characteristics of the section after improvement (ignoring the user-coded capacity effect); and

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6. One potential efficiency is a reduction in the disruptive effects of highway construction. However, because the costs of such disruption are not currently estimated by either HERS or HERS-ST, there is no need to adjust for the reduction in disruption.

4. HERS-ST's estimate of capacity after implementation of the more aggressive improvement (obtained entirely from the physical characteristics of the section without reference to the user-specified capacity effect of the original improvement).

The benefits of the replacement are then estimated by using (2) as estimated capacity without the replacement, and (2) + (4) – (c) as estimated capacity with the replacement.[7]

4.2 HERS-Designed Improvements

HERS will design improvements for any deficient section for which the user has not set the override flag in the state improvements file to one. HERS improvements are designed by the model in response to deficient section conditions. Two deficiencies – capacity and surface condition (PSR) – are considered to be "triggering" deficiencies: HERS will not consider improving a section unless at least one of these two conditions is deficient. HERS recognizes other potentially deficient section characteristics (such as lane width, shoulder type, and alignment), but will not improve a section based only on these less urgent shortcomings.

This section discusses criteria HERS uses to identify deficient sections; the types of HERS improvements and the process of designing them; and the effects of implementing these improvements on section characteristics.

4.2.1 Deficiency Criteria

HERS recognizes a section's need for improvement by comparing its characteristics to user-specified deficiency levels. HERS distinguishes up to three degrees of deficiency that might exist for eight characteristics of each highway section. The eight characteristics are:

1. Pavement condition;
2. Surface type;
3. Volume/Capacity (V/C) ratio;
4. Lane width;
5. Right shoulder width;
6. Shoulder type;
7. Horizontal alignment; and
8. Vertical alignment.

The three degrees of deficiency are identified by three user-specified levels: DL (deficiency level); SDL (serious deficiency level); and UL (unacceptability level). The roles of these three levels in the HERS improvement-selection procedure are:

1. If the DL for a particular characteristic of a section is violated, HERS will analyze the benefits and costs of potential improvements that would correct

7. A similar process is used to estimate the capacity effects of any improvement that is designated or considered for implementation in subsequent FPs.

this condition. If the resulting benefit/cost ratio of such an improvement is high enough, it may be selected to be implemented.

2. If the SDL for a particular characteristic of a section is violated, then only improvements that correct this condition are evaluated by the HERS benefit-cost analysis procedure.
3. If the user has specified that improvements are mandatory if the UL for a particular characteristic is violated, then an improvement that corrects this condition is normally selected automatically (see section 4.2.3.5, "Addressing Unacceptable Conditions: the Optional First Pass."). The B/C ratio for the improvement is considered by HERS only if the limiting constraint (whether funds available or system performance level) is insufficient to correct all such conditions.

The values used by HERS are contained in an external ASCII file (DLTBLS.DAT) for convenient user access and modification. The user may modify the DLs through the Parameter Model screens of the HERS-ST GUI. The user can access the SDL and UL settings using the GUI's "advanced mode."

4.2.2 Default Deficiency Criteria

Suggested default values for the ULs, SDLs, and DLs for the eight section characteristics are presented in Appendix A (these values were used in processing for the 2002 *C&P Report*). As indicated in the exhibits, for rural sections HERS allows separate values to be specified for three terrain types and eight combinations of functional system and average daily traffic (AADT). For urban sections, HERS allows separate values for each of five functional systems.

In the case of pavement condition (Table A-1, "Default Pavement Condition Criteria (PSR)"), SDLs are not shown, but a set of "reconstruction levels" (RLs) are. SDLs for pavement condition are not needed because all improvements involve either resurfacing or reconstruction, and, in HERS, only one of these two improvement options are considered for a section in any funding period. The pavement option considered is resurfacing unless PSR is below the RL or certain surface-type deficiencies (specified in Figure 4-2) exist.[8]

The tables in Appendix A also show User-Specified Thresholds and, in several of the tables, the design standards (DS) for rural sections used by HERS. The design standards used for median width and for curves and grades are shown in Table A-10, "Default Design Standards For Median Width (Feet)," and Table A-11, "Default Design Standards For Curves and Grades." The design standards used for urban sections are shown in Table A-12, "Default Design Standards for Urban Sections."

HERS does not use the USTs in selecting improvements; however the shoulder type USTs are used as design standards when shoulders are improved and the lane width USTs are used to specify the lane width following reconstruction of an unpaved section. HERS uses the USTs to develop some summary statistics.

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8. For medium and high-type pavement, PSR is the sole determinant of whether a section should be reconstructed; and for low-type pavement, it is the primary determinant. HERS is unable to take into account other influences on the reconstruction decision (e.g., height of the pavement crown), because they are not currently described in the HPMS database.

The three paragraphs below provide some general discussion of the default values for the unacceptability levels, deficiency levels, and serious deficiency levels, respectively, and the effects of using values that are more or less stringent.

4.2.2.1 Deficiency Levels

The DLs identify deficiencies that warrant analysis by HERS. Logically, the DLs may be set at any value between the SDLs and the design standards. Relatively relaxed DLs (i.e., specifying relatively low levels of service) will limit the number of potential improvements analyzed by HERS and decrease computation time; while more stringent DLs will require HERS to analyze a larger number of potential improvements and may permit HERS to find a more cost-effective set of improvements to be implemented. HERS users should be aware that the optimal set of DLs will actually vary with the particular objective function used (that is, the type of analysis requested) and with the size of the highway-improvement budget (the optimal DL settings will get more stringent as the budget increases). The DLs presented in Tables A-1 through A-9 are the values used in the 2002 *C&P Report*.

4.2.2.2 Serious Deficiency Levels

The SDLs are used by HERS to limit the number of alternative improvements analyzed for a given section. Logically, the SDLs may be given values between the UL values and the DL values. If all SDLs are set equal to the corresponding DLs, no more than one improvement will be analyzed for each section in a given funding period, and any improvement analyzed will address all deficiencies identified for the section. If all SDLs are set equal to the corresponding ULs, up to six different improvements may be analyzed for each section (these consist of a pavement option with or without the improve alignment option and with zero, one or two widening options). The settings used for the SDLs thus will have a significant effect on the computation time required by HERS.

The SDLs have another potentially significant effect. When an SDL is violated for a particular section for which no UL is violated, any improvement evaluated for the section must correct the specified serious deficiency. This restriction will increase the cost of improving the section, but it also decreases the likelihood that the section will be improved without correcting all serious deficiencies (it does not guarantee that all serious deficiencies will be corrected since, if mandatory improvements are enabled and an unacceptable condition develops, HERS may correct the unacceptable condition without correcting other serious deficiencies).

This second effect of the SDLs suggests that it may be appropriate to set all SDLs to the represent minimum levels of service. Many of the suggested SDL default values presented in Tables A-1 through A-9 are, in fact, set to the HPMS' minimum tolerable conditions values.

4.2.2.3 Unacceptability Levels

A review of Table A-1, "Default Pavement Condition Criteria (PSR)," indicates that the default UL values for pavement condition are slightly below the reconstruction level, and a review of Tables A-3 through A-9 indicates that the other UL values represent conditions somewhat worse than the "minimum tolerable conditions" formerly defined by the HPMS. The UL values are called into play only when the user has specified that the model shall give priority to mandatory improvements. Mandatory improvements to improve sections with conditions below the ULs are not required to pass the minimum benefit-cost ratio threshold. Mandatory improvements are not used in preparation of the *Conditions and Performance Report*.

4.2.3 HERS Improvement Types and Kinds

The highway improvements considered by HERS consist of resurfacing or pavement reconstruction, possibly combined with some type of widening and/or alignment improvement. Schematically, these improvement types can be viewed as being obtained by selecting one "improvement option" from each of the columns of Table 4-2. There are 32 possible combinations for the options in the three columns of the table, and eight possible combinations for the options in the first two columns. However, as HERS corrects shoulder deficiencies when reconstructing pavement, it makes no distinction between pavement reconstruction with or without shoulder improvements. The result is 28 different "types" of improvement, or, if the third column is ignored, seven different "kinds" of improvement.

Table 4-2. Improvement Options

Pavement	Widening	Alignment
0. Resurface	0. None	0. No change
1. Reconstruct	1. Improve shoulders	1. Improve curves
	2. Widen lanes	2. Improve grades
	3. Add lanes	3. Improve curves and grades

Table 4-2 shows three distinct alignment options: improve curves, improve grades, or improve both. In HERS, if curves (respectively, grades) are in "unacceptable" condition (as defined elsewhere in this chapter) but grades (respectively, curves) are not, then an improvement that improves curves (respectively, grades) to the design standard but does not modify grades (respectively, curves) may be selected. Otherwise, only alignment improvements that result in improving both curves and grades to the design standard are considered.

Each of the seven kinds of improvement are described briefly in Figure 4-1. Within each group, the improvements are listed in decreasing degree of aggressiveness.

HERS uses an additional set of extra-cost options to improve substandard urban freeways to design standards. The four options are: surface shoulders; improve access control to full; upgrade median type to positive barrier; and widen median to design standard. The appropriate improvements are only implemented on substandard urban freeways undergoing pavement reconstruction; sections being resurfaced are not upgraded in this manner.

The HERS model differentiates between lanes added at "Normal" and "High" cost. New lanes are added at normal cost when they do not violate the state-supplied Widening Feasibility code (WDFEAS) for the section. The user has the option of setting the Federal Override (WDFOVR) value to add lanes beyond those permitted by the state code up to the maximum lane limit (MAXLNS). These lanes are added at high cost. It is possible for a section to be improved by the addition of lanes at both cost levels: HERS reports these improvements as high cost lanes in the output statistics.

4.2.3.1 Identifying Improvements for Analysis

During each funding period, HERS is designed to make two passes over the entire set of sample sections to identify improvements that might warrant implementation. The first pass is optional and is used to identify improvements to be implemented based

A. Reconstruction

1. Reconstruction with More Lanes - Complete reconstruction with the addition of lanes to the existing section. Lanes added in excess of the state-coded widening feasibility code are added at high cost – otherwise, lanes are added at normal cost. Shoulder and drainage deficiencies are corrected.
2. Reconstruction to Wider Lanes - Complete reconstruction with wider lanes than the existing section. No additional lanes are added. Shoulder and drainage deficiencies are corrected.
3. Pavement Reconstruction - Complete reconstruction without adding or widening lanes. Shoulder width increased to design standard if feasible, and any other shoulder or drainage deficiencies are corrected.

B. Resurfacing

1. Major Widening - The addition of lanes to an existing facility. Lanes added in excess of the state-coded widening feasibility code are added at high cost – otherwise, lanes are added at normal cost. This improvement includes resurfacing the existing lanes and other minor work such as shoulder and drainage work.
2. Minor Widening - This improvement is similar to major widening except that the added width yields wider lanes or shoulders, but no additional lanes.
3. Resurfacing with Shoulder Improvements - The overlay of existing pavement plus the widening of shoulders to design standards if feasible or the complete reconstruction of shoulders to provide additional strength. A minor amount of additional right-of-way may be acquired.
4. Resurfacing - The overlay of existing pavement including bringing the shoulders up to grade including minor drainage work.

Figure 4-1. Kinds of Improvement

upon engineering criteria, regardless of their economic desirability. During the first pass, for paved sections with unacceptable present serviceability ratings for pavement condition and for unpaved sections with unacceptable surface type or lane width, HERS selects an appropriate inexpensive improvement. If sufficient funds are available, all such improvements are implemented without any B/C analysis. Otherwise B/C analysis is used to select the improvements to be implemented. Note: this optional first pass is not used in the analysis for the *C&P Report*.

During the second pass, HERS identifies additional deficiencies as well as appropriate improvements to address these deficiencies. B/C analysis is then used to determine which of these improvements to implement.

The procedures used to identify improvements during each of these passes are presented below. As the procedure used during the second pass is central to the use of B/C analysis by HERS, that procedure is described first.

4.2.3.2 Addressing Ordinary Deficiencies: the Second Pass

During the second pass, HERS identifies deficiencies on the basis of the user-specified DLs and SDLs. HERS identifies an improvement type only when a pavement or capacity deficiency exists in the current funding period. When such a deficiency exists, HERS generally will identify at least one improvement type that will address it (the exception to this rule is when the only deficiency is a capacity deficiency, and additional lanes are either not needed or cannot be added, and it is not possible to widen the section to correct any substandard shoulder or lane widths).

The procedure for identifying improvement types to address ordinary deficiencies consists of two components:

1. Identification of one (or, in some cases, two) "aggressive improvement type(s)" that will correct all identified deficiencies; and
2. Identification of any less aggressive improvement types warranting B/C analysis as possible alternatives to the first, more aggressive, improvement(s). These alternatives would address some but not all of the segment's deficiencies.

These two components of the procedure are discussed below.

4.2.3.3 Aggressive Improvement Types

The procedures for selecting pavement, width and alignment options are presented in Figure 4-2, Figure 4-3, and Figure 4-4 respectively. These three procedures, taken together, identify a set of options that define a maximum of two improvement types.

A. Reconstruct if:

1. PSR at the beginning of the funding period is less than reconstruction PSR;
2. surface type is low and deficient, and a widening option is identified; or
3. surface type is unpaved and:
   a. surface type is deficient; or
   b. a widening option is identified.

B. Otherwise resurface if:

1. PSR at the end of the funding period is deficient; or
2. a widening option is identified.

Figure 4-2. Identification of Aggressive Pavement Option

When considering pavement options, HERS decides whether resurfacing or reconstruction is appropriate based upon PSR at the beginning of the funding period analyzed. This reconstruction level is set by the user. As shown in Figure 4-2, the consideration of reconstruction can also be triggered by the inadequacy of the current surface type.

When considering widening options, HERS may select both an "add lanes" option and, if appropriate, the "widen lanes" option as well. This is the only situation in which HERS will identify two aggressive improvement types for further analysis. This can occur only when:

1. Additional lanes can be added;
2. More lanes are needed in the design year, but not now;
3. Widening lanes will increase capacity without correcting the design year capacity deficiency; and
4. Reconstruction is needed.

HERS identifies the widen lanes option whenever the PSR is deficient, widening is feasible, and either lanes are needed but cannot be added or lane width is deficient.

A. For unpaved sections:

1. A. Widen lanes if a deficiency exists in lane width or (for collectors in the lowest volume category) in sum of lane width and shoulder width.

B. For paved sections:

1. Add lanes if lanes can be added and

   a. more lanes are needed[a] or

   b. pavement requires reconstruction, and more lanes will be needed in the design year

2. B. Widen lanes if lanes can be widened and

   a. more lanes are not needed, or lanes cannot be added and

      i. lane width is deficient, and PSR is deficient; or

      ii. design hour V/C is deficient, and capacity would be increased by widening lanes[b], and lane width is less than design standard; or

   b. If PSR is deficient, and design hour V/C is not deficient but will be in the design year, and capacity would be increased by widening lanes[b], and lane width is less than the design standard, and

      i. section is an urban freeway by design type; or

      ii. the reconstruction option has been identified solely as a result of a pavement or surface type deficiency.

3. Otherwise, improve shoulders if:

   a. shoulder width is less than the design standard, widening is feasible, design hour V/C is deficient, and capacity would be increased by improving shoulders[b];

   b. shoulder width is deficient, widening is feasible, and PSR is deficient; or

   c. shoulder type is deficient and PSR is deficient.

Figure 4-3. Identification of Aggressive Widening Options

a. “More lanes are needed” means V/C is deficient both now and in the design year.

b. On some sections with initial capacity coded in the HPMS data base, widening lanes or shoulders may not result in any increase in capacity (because the calculated capacity after widening is no higher than the coded capacity). For such sections, the “widen lanes” and “improve shoulders” options do not produce any benefits recognized by HERS. For such sections, these improvements are analyzed by HERS only if they address a “serious deficiency”.

The HERS decision to widen lanes does not depend upon factors such as whether reconstruction is required, rural or urban location and whether or not the section is an urban freeway/expressway up to design standards.

When considering alignment options, HERS considers both horizontal and vertical alignment improvement for rural sections and horizontal alignment improvements for urban principal arterials. This analysis is done only for segments for which complete information about curves and/or grades by class is available (the HPMS Field Manual requires this information for rural principal and minor arterials and urban principal arterials).

A. For rural sections:

1. Improve curves and/or grades if:
   a. curves and/or grades by class are specified,
   b. any pavement or widening option is identified, and
   c. horizontal or vertical alignment is deficient.

B. For urban sections:

1. Improve curves if:
   a. curves by class are specified,
   b. reconstruction is identified, and
   c. horizontal alignment is deficient.

Figure 4-4. Identification of Aggressive Alignment Options

4.2.3.4 Less Aggressive Alternatives

After identifying one (or two) aggressive improvement types that will address all of a section's deficiencies, HERS then identifies less aggressive improvement alternatives, and uses benefit-cost analysis to choose among all the alternatives. In general, less aggressive improvements can be derived directly from the most aggressive improvement by:

1. Replace a widening option with no widening;
2. Replace a widening option with a less aggressive widening option; or
3. Replace improved alignment with no change in alignment.

Replacement rules 1 and 3 involve replacing a particular option with the corresponding "zero-level" option (as defined and numbered in Table 4-2, "Improvement Options"). If HERS had selected a single aggressive improvement type including both widening and an alignment improvement, these two replacement rules would identify up to three less aggressive alternative improvements for analysis (zero-option for widening, zero-option for alignment, and zero-option for both). If HERS had selected two aggressive improvement types for further analysis, these rules would identify up to four less aggressive alternatives, so up to six alternatives might be analyzed for some sections.

Although an exhaustive evaluation of all such alternatives may, at times, be of interest, it is likely that HERS users frequently will prefer that some of these evaluations be skipped in order to shorten run times. This is accomplished using the SDLs introduced in section 4.2.1 "Deficiency Criteria" on page 4-7. When the user-specified SDL for a section characteristic is violated, any improvement option designed to address the deficiency is treated as "required" and HERS will not analyze the zero-level alternative. If the SDL is not violated, any improvement designed to address the deficiency is treated as "non-required" or "optional," and the zero-level alternative to the option is analyzed (there is no SDL for pavement condition, since the decision on whether to reconstruct or resurface a section is primarily based on the reconstruction level. HERS does not directly compare reconstruction alternatives with resurfacing alternatives for an individual section).

Replacement rule 2 is used only in the special case in which a lower-level widening option (e.g., improve shoulders, or widen lanes) is required (because the SDL for shoulder-width or shoulder-type is violated), but a non-required higher-level widening option (e.g., widen lanes or add lanes) is included in the aggressive improvement identified by HERS. In this case, HERS considers the required lower-level widening option as an alternative to the aggressive improvement, rather than evaluating the zero-level alternative.

If the user has elected to enable ULs (unacceptability levels), and if the capacity of a section is expected to violate the user-specified UL during the expected design life for a pavement improvement being considered, a capacity improvement option is treated as a required accompaniment to that pavement improvement, regardless of whether the capacity SDL is currently being violated. In this case, the zero-level alternative widening option would not be evaluated. This requirement enables HERS to avoid a situation in which capacity becomes unacceptable at a time when resurfacing (or reconstruction) is not normally performed.

If all SDLs are set equal to the corresponding DLs, then normally only the "most aggressive" improvements identified by the procedures of Figure 4-2 through Figure 4-4 are analyzed. If the SDLs are relaxed completely (that is, the SDL for the V/C ratio is set high and all other SDLs are set to zero), all alternatives generated by replacement rules 1 and 3 are evaluated. The implications of how the user chooses to set the DL, SDL, and UL levels are discussed more fully in section 4.2.2.1 "Deficiency Levels" on page 4-9.

4.2.3.5 Addressing Unacceptable Conditions: the Optional First Pass

The user may instruct HERS to identify unacceptable conditions and accord them a greater priority for correction than serious deficiencies. This option is available on the "Run Specifications" screen of the Control Model sequence, and is titled "Give priority to mandatory improvements."

In most instances, the improvements selected to correct the unacceptable conditions will be implemented without being subject to B/C analysis. When the analysis is constrained by available funds, a portion of the available funds may be designated for the correction of unacceptable conditions. In the case of paved sections, whenever a section is found to have an unacceptable PSR, an appropriate inexpensive improvement that addresses all unacceptable conditions on the section is identified. In the case of unpaved sections, whenever a section is found to have unacceptable surface type or lane width, an appropriate inexpensive improvement that addresses all such conditions is identified. The procedure for identifying options defining these improvements is presented in Figure 4-5

Paved sections with unacceptable PSR and unpaved sections with unacceptable surface type or lane width will be referred to as sections with "triggering unacceptabilities". The procedure presented in Figure 4-5 is designed to identify all such sections and, except for the case in which the V/C ratio is unacceptable, the procedure is designed to identify the least expensive of the available HERS improvements that will correct all unacceptable conditions on such a section. In the case of an unacceptable V/C ratio, the procedure selects the most aggressive widening option warranted by the section's characteristics.

When a section has unacceptable pavement, the improvement identified by the procedure shown in Figure 4-5 will generally be selected to improve the section.[9] However, the implementation of mandatory improvements is handled slightly differently depending on the user's analytical objective, as discussed below.

A. For paved surfaces:

1. If at the end of the funding period the PSR is unacceptable:
   a. Reconstruct if surface type is low and unacceptable;
   b. Otherwise, reconstruct if at the beginning of the funding period the PSR is below the reconstruction PSR;
   c. Otherwise, resurface.
2. If resurfacing or reconstruction has been selected, then:
   a. For rural sections, improve curves and/or grades if horizontal and/or vertical alignments are unacceptable, and curves and/or grades are specified by class;
   b. For urban principal arterial, improve curves if horizontal alignment is unacceptable, and curves are specified by class;
   c. If V/C is unacceptable:
      i. Add lanes if more lanes are needed and can be added;
      ii. Widen lanes if lanes can be widened:
         • if lane width is unacceptable; or
         •. if lane width is less than the design standard, and widening lanes will increase capacity, and widening shoulders will not make V/C acceptable;
      iii. Otherwise, improve shoulders if shoulder width is less than design standard and shoulders can be widened and widening shoulders will increase capacity.
   d. Widen lanes if lane width is unacceptable and lanes can be widened;
   e. Improve shoulders if shoulder width is unacceptable and widening is feasible;
   f. Improve shoulders if shoulder type is unacceptable.

A. For unpaved surface types:

1. Widen lanes and reconstruct if lane width is unacceptable and lanes can be widened;
2. Reconstruct if surface type is unacceptable.

Figure 4-5. Identification of Improvement Options for Addressing Unacceptable Conditions

4.2.3.6 Determining the Number of Lanes to Add

An important consideration when evaluating an "Add Lanes" improvement is the number of lanes being added, as this both determines the cost of the improvement and is the prime factor governing the user cost benefits of the improvement. The HERS version 4.n model may consider either one or as many as five different possibilities

9. It should be noted that (as currently implemented), for paved sections, only pavement-related conditions trigger the correction of unacceptable conditions; but, when unacceptable pavement conditions are corrected, all other unacceptable conditions are corrected as well. This procedure, in conjunction with the procedure for addressing serious deficiencies, guarantees that any non-pavement-related unacceptable conditions will be corrected whenever the pavement of a section is improved. However, except when warranted by benefit-cost analysis, these conditions will normally not be corrected as long as the section's pavement remains in reasonably good condition.

when adding lanes to a section. This latter option is called the "incremental number of lanes" option. The model determines the number of possible lane options in two steps: first, it determines the number of lanes required in the design year; and second, it identifies as many as four additional lane options. HERS then designs potential add lane improvements for each of the identified options for evaluation via cost-benefit analysis.

4.2.3.6.1 Design Year Lane Requirements

When estimating the future traffic volume for the purpose of determining lane requirements, HERS does not apply demand elasticity.[10] Instead it projects the geometric rate of growth AADTGR (see Equation 5.55 on p. 5-53) as in Equation 5.56 on p. 5-54, using the "fully elasticized" AADT *at the beginning* of the current funding period for VADJ, and the number of years from the time of that AADT to the "design year" as the "length of the funding period" (LFP).[11] The design year is the length of the design period (specified by the user in the parameter file; the default value is 20 years) from the point of implementing the improvement, which is at the middle of the current funding period.

The design number of lanes normally is the minimum number necessary to achieve a design year volume/capacity ratio that satisfies the user-specified widening standard.[12] The capacity used in this ratio is the peak capacity that would be produced by adding the specified number of lanes. The design number of additional lanes (DNADDL) is the total number of lanes in the design year minus existing lanes, and may be reduced as a result of limitations on widening feasibility or on the maximum numbers of lanes allowed. This number is user-specified for each functional class and is limited to 99 (the value used for the 2002 *C&P Report*). Also, HERS limits sections with stop signs to a maximum of two through lanes in each direction.

If the user has disabled the incremental number of lanes option, HERS only evaluates adding the design number of additional lanes.

4.2.3.6.2 Additional Lane Options

When the user has enabled the incremental number of lanes option, the five options HERS may identify for a two-way road (where HERS adds lanes in pairs) are:

1. Two lanes (when the section's widening feasibility code allows the addition of exactly two normal cost lanes and the design number of additional lanes (DNADDL) is not equal to two);
2. Half of DNADDL;
3. Three quarters of DNADDL;
4. DNADDL; and
5. DNADDL plus two (depending on capacity criteria).

For one-way roads, where HERS adds lanes singly, the options become:

10. In one sense, this mimics the non-elastic calculations of highway engineers. Practically, it avoids the computationally intense attempt to solve for elasticity when the future capacity is unknown.
11. The default value for the design period is 20 years, which is presumed to begin at the time the improvement is implemented. Thus, for the initial five-year funding period, the improvement is implemented at year 2.5, the design year is year 22.5, and the exponent used is 22.5.
12. When addressing unacceptable conditions, the unacceptability level is used instead of the widening standard.

1. One or two lanes (the maximum number of normal cost lanes permitted by the section's widening feasibility providing that number is less than DNADDL);
2. Half of DNADDL;
3. Three quarters of DNADDL;
4. DNADDL; and
5. DNADDL plus one (depending on capacity criteria).

HERS doesn't add fractional lanes, rounds the numbers in options two and three, and doesn't consider duplicate cases. In many cases HERS will determine that only one option is suitable for benefit-cost analysis.

Option one is designed to prompt HERS to evaluate the lower cost option of adding only lanes at normal cost, and comparing this with options where some lanes are added at high cost. For two-way sections, this means a widening feasibility (WDFEAS) of four; for one-way sections, WDFEAS may be either three or four. This option becomes moot when the widening feasibilty override (for the functional class) is set at less than five -- in that instance, DNADDL would be limited to the number of normal cost lanes permitted by the section's widening feasibility code.

For HERS to consider options two and three, the options must identify numbers of additional lanes which are distinct from DNADDL and option one (if option one is identified). They must also be distinct from each other.

Option four is the design number of additional lanes. It is always identified as a potential add lanes improvement.

Option five compares three predicted capacities: the capacity needed to satisfy the forecast traffic on the section (NEEDCAP); the capacity predicted after adding DNADDL lanes (NEWCAP); and the capacity predicted after adding DNADDL less one or two lanes (TEMPCAP, for one-way and two-way roads, respectively). As an artifact of the procedure which determines DNADDL, NEWCAP will be greater than NEEDCAP, which in turn is greater than TEMPCAP. If the difference between NEWCAP and NEEDCAP is less than the difference between NEEDCAP and TEMPCAP, HERS will consider option five.

4.2.3.6.3 Examples of Lane Option Logic

Table 4-3 illustrates how HERS applies the above-described logic to the problem of designing add lane improvements. Each block describes the parameters for a section and the number of lanes added for each active option. Inactive options (because they generate duplicate lane values or their governing conditions are not met) are not included in the block. All the examples are two-way highways, and as a simplification, all the lanes in the examples have a capacity of 1000. The widening feasibility override is set to five, allowing HERS to add lanes beyond those permitted by each section's WDFEAS code, but at high cost. NEWCAP represents the capacity of the existing lanes plus the minimum number of lanes needed to meet design year capacity requirement (in NEEDCAP). That minimum number of lanes is shown as option four. (Thus the existing number of lanes equals NEEDCAP divided by 1000 minus the lanes added under option four.) TEMPCAP is the capacity after adding two fewer lanes than option four.

Table 4-3. Designing Add Lanes Improvements

WDFEAS	NEEDCAP	NEWCAP	TEMPCAP	Qualifying Option	Normal Cost Lanes Added	High Cost Lanes Added	Total Lanes Added
4	11,500	12,000	10,000	1	2	0	2
				2	2	2	4
				3	2	4	6
				4	2	6	8
				5	2	8	10
5	11,500	12,000	10,000	2	4	0	4
				3	6	0	6
				4	8	0	8
				5	10	0	10
1	11,500	12,000	10,000	2	0	4	4
				3	0	6	6
				4	0	8	8
				5	0	10	10
4	7500	8000	6000	1	2	0	2
				4	2	2	4
				5	2	4	6
5	6500	8000	6000	2	2	0	2
				4	4	0	4

The first block is a full-blown example: all the add lane options are active. Option four indicates that adding eight lanes would satisfy the NEEDCAP requirement. Because WDFEAS is four, two lanes can be added at normal cost, so option one will be considered. Options two and three duplicate none of the other options, and will also be evaluated. And since NEEDCAP is closer to NEWCAP than TEMPCAP, HERS will also consider option five. Note that each option adds two lanes at normal cost, with additional lanes added at higher cost.

The second block illustrates a section which differs from the first in only one circumstance: it's widening feasibility is five, meaning that 3 or more lanes can be added at normal cost. Option one is not considered; HERS only designs and evaluates improvements adding four, six, eight and ten lanes. All the lanes are added at normal cost.

The third block shows the same section with a widening feasibility of one which, in concert with the override code of five, permits HERS to only add lanes at high cost. HERS again designs and evaluates improvements adding four, six, eight and ten lanes, but this time at high cost.

The fourth block represents a four lane section where the additional lanes needed for the design year capacity are four (option four). Because WDFEAS is 4, two lanes can be added at normal cost, so HERS activates option one. HERS discards options two and three since, after rounding, they would duplicate options one and four. Option five is also activated due to the relative values of the three capacities. So for this section, HERS will design potential improvements that add two, four, or six lanes.

The fifth block presents a section similar to the fourth block, except that WDFEAS is five (allowing three or more lanes to be added at normal cost), and the needed capacity is less. Because WDFEAS is no longer four, HERS discards option one. Option two, at half the design year number of additional lanes, is no longer a duplicate of option one, so HERS activates it as two normal cost lanes. The conditions for option five do not hold, so HERS designs two potential add lanes improvements for this section, adding two or four lanes.

4.2.4 Effects of HERS Improvements

The effects of each HERS improvement are simulated by changing the description of the characteristics of the sample section. When evaluating potential improvements, HERS builds a temporary description of the section for each of the candidate improvements (when analysis extends for more than a single funding period, HERS builds a series of descriptions extending to the end of the benefit-cost analysis period). If HERS implements an improvement at the end of processing for a funding period, the altered description is saved for use in the following funding period.

HERS analyzes the effects of all improvements as if they are implemented instantaneously at the middle of a funding period instead of being spread throughout the funding period. Accordingly, by the end of a funding period, the PSR of a reconstructed section shows the effect of one-half period of pavement deterioration. The disruptive effects of improvements are not analyzed. Sections which do not undergo improvement during a funding period also have their section descriptions updated to reflect forecast changes in PSR and traffic volume. This “unimproved condition” is used as a base case in benefit-cost analysis.

Most of the effects of improvements on the “section data items” that form this description are shown in Table 4-4. The widening options in this exhibit are assumed to be accomplished without any change in rush-hour parking rules. Effects that occur only when lanes are added to rural sections are shown separately in Table 4-5, “Additional Effects of Adding Lanes on Data Items for Rural Sections.” The effects of alignment improvements on alignment-related data items (curves and grades, passing sight distance, and weighted design speed) and on pavement condition are presented in Table 4-6.

The additional effects of improving substandard conditions on urban freeways are presented in Table 4-7, “Effects of Addressing Substandard Conditions on Urban Freeways.” In HERS, the changes shown in Table 4-7 are implemented, if feasible, whenever a substandard urban freeway undergoes pavement reconstruction.

The effects of improvements on widening feasibility are presented in Table 4-8, “Widening Feasibility Code Adjustments.” Generally, when widening improvements are made, widening feasibility for future improvements is reduced. The exception is sections coded as having unlimited widening feasibility, for which widening feasibil-

Table 4-4. Effects of Improvements on Section Data Items -- All Sections[a]

Section Attributes	Improvement Type						
	Reconstruct With More Lanes (High or Normal Cost)	Reconstruct With Wider Lanes	Reconstruct Pavement	Major Widening (High or Normal Cost)	Minor Widening	Resurface W/Shoulder Improvement	Resurface Pavement
Number of Lanes[b]	Design Number	NC	NC	Design Number	NC	NC	NC
Lane Width	DS	DS	NC[c]	DS	DS	NC	NC
Shoulder Type[d]	Existing or UST1	Existing or UST1	Existing or UST1	Existing or UST1	Existing or UST1	Existing or UST1	NC
Right Shoulder Width[d]	DS	DS	DS[e]	DS	DS	DS[e]	NC
Pavement Condition (PSR Value)[f]	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate
Pavement Thickness	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate
SN or D	NC or Increase	NC or Increase	NC or Increase	NC or Increase	NC or Increase	NC or Increase	NC or Increase
Surface Type[g]	DS	DS	DS	DS	DS	DS	DS
Peak Capacity	Recalculate[h]	Recalculate[h]	NC[i]	Recalculate[h]	Recalculate[h]	NC[i]	NC

a. NC = No Change, and DS = set to Design Standard.

b. The design number of lanes is the number of lanes needed to accommodate projected traffic in the design year, and which would be added if widening were not constrained. The two constraints are widening feasibility and the maximum number of lanes allowed. This last number is user-specified and can vary with functional class. For the 1999 *C&P Report*, the maximum number of lanes for all functional classes was 99.

c. For an unpaved section the improvement reconstruct pavement results in paved lane widths equal to the user specified threshold.

d. Curbed sections remain curbed (with zero shoulder width) after improvements.

e. Shoulder only widened if feasible.

f. Changes in PSR specified in Table II-14 of HPMS/AP *Technical Manual*.

g. If low type pavement exists, resurfacing does not change the pavement type.

h. No change if recalculated capacity is lower than original capacity.

i. If the shoulders are widened, the value is recalculated.

Table 4-5. Additional Effects of Adding Lanes on Data Items for Rural Sections

Data Item	Effect
Median Width	Widen to design standard or to the extent feasible.
Median Type	Set to unprotected if median width is widened and median type is currently “none.”
Access Control	If median is added and access control is not full, set to partial.

Table 4-6. Effects on Section Data Items of Alignment Improvements

Data Item	Effect
Grades	Substandard grades are improved to design standard.
Curves	Substandard curves are lengthened and improved to design standard.[a]
Passing Sight Distance	(For rural two-lane highways only) improve to typical passing sight distance (from 1978 data).
Weighted Design Speed	Recalculate. If no data on curves by class, increase by 5 m.p.h.[b]
Pavement Condition	Obtain as a weighted average of the PSR on the portion of the section with modified alignment[c] and the PSR indicated in Exhibit 3.3 for the remainder of the section.

a. The procedure used for determining the extent to which curves are lengthened is presented in Chapter 5.

b. HERS contains code for adjusting weighted design speed when there is no data on curves by class, but HERS does not consider horizontal alignment improvements when these data are not available.

c. The portion of the section with modified alignment equals the sum of the portions with substandard grades or curves (after lengthening) but is no greater than the length of the section.

Table 4-7. Effects of Addressing Substandard Conditions on Urban Freeways

Data Item	Effect
Shoulder Type	Improve to surfaced.
Access Control	Improve to full control if feasible.[a]
Median Type	Improve to positive barrier.
Median Width	Improve to design standard if feasible.[b]

a. Improvement to full control is assumed to require one lane of right-of-way.

b. Improvement of median width to design standard is assumed to require one lane of right-of-way.

ity is never reduced. The values shown assume that the override factor WDFOVR is set to 5, thus allowing widening in excess of the limits indicated by WDFEAS. However, the urban freeway upgrade and rural section upgrades are not affected by WDFOVR, and WDFEAS must have a value of at least 3 for an upgrade to be implemented. For these two upgrades, note that WDFEAS is checked after it has already been adjusted for the "main" improvement (see section 4.3 "The Widening Feasibility Model" on page 4-26 for additional discussion).

4.2.4.1 The Effects of Improvements on Pavement Thickness

This section discusses the HERS procedure for estimating pavement thickness resulting from resurfacing and reconstruction and for obtaining the corresponding structural number (*SN*) for flexible pavement. As discussed in section 5.1, "The Pavement Deterioration Model," *SN* is one of the influences on the deterioration rate of flexible pavement, and the deterioration rate of rigid pavement depends directly on pavement thickness. Additionally, the cost of alignment improvements is affected by pavement thickness.

In HERS, the design life of a pavement normally is taken to be twenty years. This value can be modified by the user; however, as pavement thickness is a function of the number of ESALS forecast during the design period, modifying this variable will affect pavement thickness (and hence pavement durability). Resurfacing or recon-

Table 4-8. Widening Feasibility Code Adjustments

Original WDFEAS Code	WDFEAS Code After Improvement						
	Resurface	Resurface with Improved Shoulders	Recon-struct	Widen Lanes[a]	Add Lanes[b]	Urban Freeway Upgrade[c]	Rural Section Upgrade[d]
1 (no widening)	1	1	1	1	1	NF	NF
2 (partial lane)	2	2 or 1[e]	2 or 1[e]	1	1	NF	NF
3 (one lane)	3	3 or 2[e]	3 or 2[e]	2	1	1[f]	1
4 (two lanes)	4	4	4	3	3 or 1[g]	4, 3, or 1[h]	NA[i]
5 (three or more lanes)	5	5	5	5	5	5	5
where: NF = Not Feasible (the improvement is not made, and WDFEAS is not adjusted); NA = Not Applicable.							

a. The adjustment is the same whether the section is resurfaced or reconstructed.

b. The adjustment is the same whether the section is resurfaced or reconstructed, and without regard for whether the lanes are added at normal or high cost.

c. Applies when correcting substandard conditions on urban freeways undergoing reconstruction. The model first tries to improve access control, and then to widen the median to the design standard. Neither improvement is implemented (and WDFEAS is not adjusted) if the condition is not substandard.

d. For rural sections when lanes are added, the model will widen the median and improve access control to "partial" if feasible. Unlike the urban upgrade, a single feasibility test (and adjustment) is made for both improvements.

e. If the shoulder is not curbed and is below the design standard, it is widened to and WDFEAS reduced.

f. Only one improvement is implemented. Access control is preferred -- the median will only be widened if access control is already full.

g. If two lanes are added, the WDFEAS code is adjusted to 1 (no widening feasible). If one lane is added, the WDFEAS code is adjusted to 3 (one lane may be added).

h. Either, neither, or both of the two improvements may be needed or implemented.

i. This value will never be tested for the rural upgrade, as a WDFEAS of 4 would have been reduced as a result of the added lane(s).

struction cost will be affected only to the extent that some portion of the section has its alignment improved.

The following subsections present the values of pavement thickness for reconstruction, simple resurfacing, and resurfacing and widening; and a final subsection presents the structural numbers used by HERS for reconstructed and resurfaced flexible pavements.

4.2.4.1.1 Reconstruction

Assuming that the reconstructed pavement is designed and constructed as a new pavement structure, pavement thickness is a function of pavement material and traffic load. HERS assumes that reconstruction of either rigid or composite (flexible over rigid) pavement is performed with rigid pavement, and that reconstruction of flexible pavement uses flexible pavement. Thicknesses used by HERS for reconstruction of flexible (asphaltic concrete) pavements to a medium or high-type design standard are shown in Table 4-9 as are thicknesses for reconstruction of rigid (Portland cement concrete) pavements. For low-type flexible pavement, only a surface treatment is used.

Table 4-9. Pavement Thickness After Improvement (Inches)

Forecast ESALs over Design Life	Pavement Type	
	Flexible[a b c]	Rigid[d]
≤ 50,000	1.5	6.5
50,001 - 150,000	2.5	6.5
150,001 - 500,000	3.0	6.5
500,001 - 2,000,000	4.0	8.0
2,000,001 - 7,000,000	5.0	9.5
> 7,000,000	5.5	10.5

a. American Association of State Highway and Transportation Officials, *AASHTO Guide for Design of Pavement Structures*, Washington, D.C., 1986.

b. Thickness shown for flexible pavements are also used for resurfacing flexible pavements with a flexible overlay.

c. For low-type pavement, assume a surface treatment only.

d. E.J. Yoder and M.W. Witczak, *Principles of Pavement Design*, John Wiley, New York City, 1975.

4.2.4.1.2 Simple Resurfacing

HERS assumes that resurfacing is always performed using a flexible overlay. For flexible overlays over flexible, composite, or rigid pavement, the overlay thickness used by HERS varies with traffic load in the same way as for reconstruction with flexible pavement. These thicknesses are shown in Table 4-9.

4.2.4.1.3 Resurfacing with Widening Improvements

When resurfacing is combined with widening improvements, some part of the improved roadway will be built on land that is not already paved. In general, the newly paved area will be structurally compatible with the resurfaced roadway. HERS treats resurfacing with widening improvements as producing a single roadway whose characteristics are those of the original roadway after resurfacing.

4.2.4.2 The Effects of Improvements on Structural Number

HERS assumes that resurfacing or reconstruction never reduces the structural number (*SN*) of flexible pavement but may increase its value. To do this, a value of *SN* is obtained using an equation that approximates the relationship between *SN* and pavement thickness presented in Table IV-3 of the HPMS *Field Manual*[13]. This equation is:

$$SN = NEWSNC_1 + NEWSNC_2 \times D_f \qquad \textbf{Eq. 4.1}$$

where:

13. U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System *Field Manual*, Washington, D.C., Table IV-2, December 1, 1987.

$NEWSNC_1$	=	First NEWSNC entry from PARAMS.DAT, default value is 1.5;
$NEWSNC_2$	=	Second NEWSNC entry from PARAMS.DAT, default value is 0.75; and
D_f	=	Pavement thickness, in inches.

If the resulting value is less than the original value of *SN* coded for the section, *SN* is set to that value.

4.2.4.3 The Effects of Improvements on PSR

When pavement undergoes reconstruction, HERS sets its PSR to a level determined by the section's location and surface type. These values, *PSRREC*, may be set by the user. Table 4-10 lists the default values.

Table 4-10. PSR Values After Reconstruction

Surface Type	Rural	Urban
High Flexible	4.6	4.6
High Rigid	4.6	4.6
Intermediate	4.4	4.4
Low	4.2	4.2

For sections being resurfaced, HERS adds an increment to the PSR at the time of the improvement. This augmented PSR value is limited to maximum PSR values. These values, *PSRINC* and *PSRRMX*, may be adjusted by the user. The default values for incrementing PSR are shown in Table 4-11 and the default maximum PSR limits are shown in Table 4-12.

Table 4-11. Increase in PSR After Resurfacing

Surface Type	Rural	Urban
High Flexible	1.8	1.8
High Rigid	1.8	1.8
Intermediate	1.8	1.8
Low	1.8	1.8

Table 4-12. Maximum PSR After Resurfacing

Surface Type	Rural	Urban
High Flexible	4.3	4.3
High Rigid	4.3	4.3
Intermediate	4.2	4.2
Low	4.0	4.0

4.2.4.4 The Effects of Alignment Improvements on Pavement Characteristics

For any section, an improvement that combines pavement reconstruction with alignment improvements results in producing newly reconstructed pavement on the entire section. Such improvements produce a single type of pavement and a single PSR for the entire section.

On the other hand, improvements that combine resurfacing with alignment improvements produce a single PSR only in the (relatively rare) case in which the alignment of the entire section is improved. More commonly, such improvements produce one PSR for the portion of the section on which alignment does not change and a higher PSR on the portion that is reconstructed on a modified alignment. Furthermore, resurfacing of rigid or composite pavement is presumed to be performed with a flexible overlay (producing composite pavement), while the adjoining reconstructed pavement is presumed to be rigid. For both cases, HERS obtains a single combined PSR for the section by taking a weighted average of the PSRs on the two portions of the section, using the lengths of these portions of the section as weights. For the case in which part of the section receives a flexible overlay on composite or rigid pavement and part is reconstructed with rigid pavement, HERS uses the relative length of the two portions of the section to determine whether to treat the section as having rigid or composite pavement.

4.2.4.5 Correcting Substandard Conditions on Urban Freeways

HERS considers an urban freeway substandard if (a) it is an Interstate or Other Freeways and Expressways (that is, functional class is 11 or 12), and (b) any one of the four deficiencies listed below applies:

- the shoulders are unsurfaced;
- access control is not full
- the median type is not positive barrier; or
- the median width is less than the design standard for urban freeways and expressways by design.

The default value for the urban median width design standard is set to 20 feet.

HERS will correct these deficiencies only on urban freeways which are being reconstructed. Improving access control to full and improving the median width to the design standard each require a lane of right-of-way as coded in the section's widening feasibility (WDFEAS) data item (this data item is part of the section's HPMS input record). If the availability of right-of-way is limited, precedence is given first to adding lanes, then to improving access control, and last to improving median width.

4.3 The Widening Feasibility Model

Six of the seven major HERS improvement options involve increasing the width of the roadway: adding lanes, widening lanes, and improving shoulders[14]. Additionally, widening the median and increasing access control are two upgrades which may be performed on rural sections (when lanes are added) and substandard urban freeways (when they undergo reconstruction) and which also increase the roadway width. "Widening feasibility" refers to the potential for increasing the total width of a particular section. HERS tracks the feasibility of widening each section, and updates the information whenever the section is improved. HERS uses the interaction of system

14. Improving shoulders does not always increase width.

and section-specific constraints to determine first, whether widening improvements can be implemented, and second, whether additional lanes will be added at "normal" or "high" cost (for information about improvements which widen the roadway, see Table 4-4 on page 4-21).

HERS also uses the widening feasibility model to determine whether sections undergoing alignment improvement are re-alighned at high or low cost.

There are four factors in HERS which limit the potential width of any section. First, the user specifies the maximum number of lanes (MAXLNS) allowed for each of the functional classes. The number may be as large as 99. It is applied only when determining the number of lanes to be added to a section; it is not used in determining the feasibility of widening existing lanes, widening shoulders or medians, or in improving access control. HERS does not remove lanes from existing highways in order to meet this limit.

Second, HERS will always build to an even number of lanes. Sections with an even number of existing lanes will receive additional lanes in even-numbered increments. Sections with an odd number of existing lanes will receive an odd number of lanes the first time HERS adds lanes to the section, and an even number of lanes should more lanes be added in a subsequent funding period.

Third, each section in the HPMS database includes a Widening Feasibility (WDFEAS) code indicating the extent to which the existing road may be widened. This state-supplied code reflects physical features along the section such as severe terrain, cemeteries and park land, and non-expendable buildings (large office buildings, shopping centers, etc.). It does not reflect restrictions due to current right-of-way, State widening practices, politics, or expendable buildings (single-family residences, barns, private garages, etc.). The widening feasibility codes are described in Table 4-13.

Table 4-13. Widening Feasibility Codes

Code	Description
1	No widening is feasible
2	Partial lane may be added
3	One lane may be added
4	Two lanes may be added
5	Three or more lanes may be added

Fourth, the user specifies a system-wide Widening Feasibility Override (WDFOVR) code which corresponds to the widening feasibility codes in Table 4-13. In HERS-ST, the user may specify separate widening feasibility overrides for each functional system instead of being limited to a single override value for the entire system being analyzed (via the "Improvement Parameter" screen of Parameter Data). When the WDFOVR code is higher than a section's WDFEAS code, HERS may consider additional widening options which would ordinarily be precluded by the WDFEAS value. Lanes that are added up to the level specified by WDFEAS are treated as "normal cost" lanes. Additional lanes added based on the WDFOVR code are treated as "high cost" lanes, and are priced separately in the improvement cost file. High cost lanes are intended to represent extraordinary measures that could be taken to provide additional capacity such as double-decking a freeway, or constructing a new facility on a parallel route. Normal and high cost lanes are reported separately in HERS output.

The interplay of WDFEAS and WDFOVR is shown in Table 4-14. Each table entry lists the widening improvements HERS will consider for a section of the given widening feasibility code (WDFEAS, by column) for a specific value of the system variable WDFOVR (by row).

Table 4-14. The Role of WDFOVR in Widening

WDFOVR	Widening Feasibility Code (WDFEAS)				
	1	2	3	4	5
1		SH, WL	+1 NCL[a], SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
2	SH, WL	SH, WL	+1 NCL[a], SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
3	+1 HCL, SH, WL	+1 HCL, SH, WL	+1 NCL[a], SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
4	+1 or 2 HCLs[b], SH, WL	+1 or 2 HCLs[b], SH, WL	+1 NCL[a] or +2 HCLs, SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
5	+ HCLs, SH, WL	+ HCLs, SH, WL	+1 NCL[a] and HCLs, SH, WL, Urb, Rur	+1 or 2 NCLs[a] and HCLs, SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur

where: SH = widen shoulders; WL = widen lanes; NCL = add normal cost lane(s); HCL = add high cost lane(s); Urb = on Urban freeways by design: improve access control to full and widen median to design standard; Rur = on Rural sections with added lanes: widen median and upgrade access control to partial.

a. When the existing facility has an odd number of lanes, add one normal cost lane.

b. When the existing facility has an odd number of lanes, add one high cost lane.

Setting the WDFOVR code to 1 is the equivalent of disabling the override feature, so that each section's WDFEAS code alone determines the widening options which HERS will consider. This case is illustrated in the first row of Table 4-14. In this situation, if WDFEAS for a section is coded as 1, no widening is considered, while if WDFEAS equals 2, HERS will consider widening the shoulders and/or lanes. If WDFEAS is coded as 3, 4, or 5, HERS may also consider adding normal cost lanes, improving access control, and widening medians. When WDFEAS is coded as 3, HERS will only consider adding a lane when the existing facility has an odd number of lanes. When WDFEAS is coded as 4, HERS will consider adding one lane to a facility with an odd number of lanes, or adding two lanes to a facility with an even number of lanes.

Setting the WDFOVR code higher than 1 causes HERS to consider additional improvement options, including high cost lanes in some cases. Note that the "Rur" and "Urb" values in Table 4-14 are the same in each column. This occurs because WDFOVR is not used in assessing whether the median width and access control upgrades can be made to rural sections receiving additional lanes and substandard urban freeways undergoing reconstruction. Note also that HERS will not add lanes in excess of the MAXLNS value, regardless of how the WDFEAS or WDFOVR variables are coded.

When evaluating improvements, HERS typically uses the initial WDFEAS value at the beginning of the funding period to determine widening feasibility. However, when considering supplemental improvements, the WDFEAS value may first be adjusted downward. On rural sections receiving additional lanes and substandard urban freeways being reconstructed, the main improvement may consume all of the space available, and could preclude any additional upgrades to medians or access control that HERS might otherwise have considered. To address these situations, HERS evaluates supplemental upgrades based on a reduced WDFEAS value that factors in the effect of the main improvement on the initial WDFEAS value. The WDFEAS values shown in Table 4-14 represent the adjusted codes.

For example, a three-lane rural section with an initial WDFEAS of 3 might be resurfaced and have one lane added. Adding a lane would result in reducing WDFEAS to 1, so supplemental rural upgrades would not be considered. This reduction in WDFEAS values is why the “Rur” value doesn’t appear in Table 4-14 in the column where WDFEAS equals 4. HERS only considers median width and access control upgrades to rural sections when lanes are added. If the WDFEAS value at the beginning of the funding period was 4, adding one or two lanes would reduce the WDFEAS code to 3 or 1, respectively. Therefore, for any case in which HERS would be considering median width and access control upgrades to rural sections, WDFEAS could not equal 4 (if the initial WDFEAS value was 5, it would remain 5 after adding lanes).

HERS updates WDFEAS in response to improvements on the section. See Table 4-8, “Widening Feasibility Code Adjustments,” for the effects of improvements on WDFEAS.

For the 2002 *C&P Report*, the maximum number of lanes was set to 99 for all functional classes. The effect of setting MAXLNS to such a high number was to effectively eliminate it as a factor in regulating roadway width, leaving each section’s WDFEAS value and the WDFOVR override value to determine widening limits. WDFOVR was set to 1, which precluded HERS from adding high cost lanes to any section.[15]

4.4 The Capacity Model

The HERS capacity model has two functions. The first is the calculation of section capacity; the second is the calculation of the number of lanes needed to accommodate the projected traffic volume in the design year (that is, how many additional lanes are needed).

15. This applies to the baseline run for the economic efficiency scenario and most of the over 400 runs executed for the *C&P Report*. Some of the runs were executed with WDFOVR set to 5.

4.4.1 Capacity

HERS capacity routines are based upon Appendix N, "Procedures for Estimating Highway Capacity," of the *HPMS Field Manual*. Appendix N was revised in February 2002 and incorporates algorithms from the *Highway Capacity Manual 2000* [16].

For each section, HERS develops separate estimates of capacity for the peak and offpeak periods; and the peak-period estimates are developed separately for the peak direction and the opposite, or "counterpeak," direction. These three capacities are referred to as peak, counterpeak, and offpeak capacity. Differences in the three capacities result primarily from differences in the number of available travel lanes.

Corresponding to the three capacities, the three sets of lanes are referred to as peak, counterpeak, and offpeak lanes. Peak and counterpeak lanes represent lanes in one direction only; while offpeak lanes represent lanes in both directions.

Offpeak capacity is estimated using the coded value of the number of through lanes in the offpeak period; and peak capacity is estimated using the coded value of peak lanes. The latter value represents total through lanes for rural two- and three-lane roads and it represents peak-direction lanes for all other sections.

For sections with a peak-period directional factor that is less than 1.0, HERS obtaines the number of counterpeak lanes by subtracting the number of peak lanes from the sum of offpeak lanes and an estimate of the number of extra travel lanes (if any) available during the peak period. For sections with surfaced shoulders, the maximum number of *total* peak-period lanes is assumed to equal twice the number of peak lanes. For curbed sections, the maximum number of *extra* peak-period lanes is assumed to equal the number of sides on which peak parking is not allowed. In both cases, the number of extra peak-period lanes is reduced, if necessary, to guarantee that the fraction of lanes in the counterpeak direction is no higher than the minimum number necessary to keep congestion in the counterpeak direction lower than congestion in the peak direction. Thus, the number of counterpeak lanes is never greater than the number of peak lanes, and it frequently is smaller.

For two-way sections, the three capacities also reflect three different directional factors. For peak capacity, the coded directional factor is used (this value represents the percentage of traffic flowing in the peak direction during the design hour). For counterpeak capacity, one minus this value is used. For offpeak capacity on two-way sections, more balanced traffic flow is assumed, and the "offpeak directional factor" is usually set to 0.5.[17]

HERS allows the user to specify whether to use the estimates of peak capacity produced by the above process or the values coded in the HPMS record. If the HPMS file has been processed by a version of the submittal software that uses capacity procedures based on the 1994 and 1997 HCM, the two sets of estimates will be essentially the same. If asked to use peak capacities that differ from those derived by the above procedure, then, for each section, HERS uses the ratio of the coded peak capacity to the internally derived peak capacity as a scale factor. This factor, referred to as the

16. Transportation Research Board, *Highway Capacity Manual*, Special Report 209. Third Edition. Washington, D.C., 2000. The TRB refers to this as the *Highway Capacity Manual 2000*.
17. The exception occurs for sections with an odd number of total lanes in the offpeak period. For these sections, the fraction of total lanes in the direction with the higher number of lanes is determined. The offpeak directional factor is then set to the lower of this value and the peak-period directional factor.

"capacity ratio" (*CRATIO*), is then used to adjust the internally derived estimates of offpeak and counterpeak capacity to produce values that are consistent with the coded value of peak capacity. That is, HERS uses *CRATIO* to ensure that the differential between the supplied and calculated capacity is carried through subsequent capacity calculations. If HERS is asked to use the internally generated capacities, the capacity ratios are set to 1.0

4.4.2 Effects of Capacity Improvements

The capacity effects of any improvement that may affect capacity are estimated by:

1. Using the capacity procedure to obtain new estimates of peak, offpeak, and counterpeak capacity; and
2. Multiplying these values by the capacity ratio *CRATIO* to produce estimates that are consistent with the capacity values used prior to implementing the improvement.

Chapter 5:

Estimation of Impacts

This chapter discusses the way HERS models discrete processes: pavement wear, vehicle operating costs, crash costs, traffic forecasts, speed calculation, travel time costs, demand elasticity, agency costs, and external costs. All of these processes are affected by the implementation of an improvement or the passage of time on an unimproved section.

HERS distinguishes the following components of user costs: travel time costs, vehicle operating costs, and safety costs, which includes both property damage and personal injury. Within the context of the demand elasticity model, these costs make up the user price. User benefits are simply the difference in costs between two predicted future states of the section under consideration: typically, an improvement will lower user costs, producing a benefit. User costs are calculated per vehicle mile of travel; total user costs are a product of user costs per vehicle mile times section length times AADT.

5.1 The Pavement Deterioration Model

HERS models pavement wear as a function of traffic and environment. First, HERS calculates the effects of vehicular traffic on a section's PSR. Then, HERS figures both a minimum and a maximum rate of deterioration. The minimum rate is designed to reflect the effects of weather. The maximum rate of deterioration is designed to limit deterioration on sections with low structural numbers[1]. HERS applies these limits to the PSR value (which reflects pavement wear due to traffic) to arrive at a forecast pavement condition. HERS does not deteriorate unpaved sections, and roads without reported truck traffic are deteriorated at the minimum rate.

5.1.1 Equivalent Single-Axle Loads

Except for roads with relatively light traffic volumes, the rate of pavement deterioration is dependent primarily on the number of 18,000 pound (18 kip) equivalent single-axle loads (ESALs). For any time period, ESALs on the most heavily traveled lane of each sample section are estimated using

- total traffic for the time period;
- percentages of single unit trucks and combination trucks on the sample section;
- an 18-kip equivalent load factor; and

1. Structural numbers (SN), which range from 1.0 to 6.0, indicate the strength of pavement. Sections whose SN is in the range from 1.0 through 3.0 are considered "light".

- a lane-load adjustment factor.

The 18-kip equivalent load factor is a function of pavement type, functional class, and truck type; values for this factor are given in Table 5-1. The lane load adjustment factor provides an estimate of the percentage of trucks that travel in the lane most heavily used by trucks as a function of the number of lanes in one direction; these values follow the AASHTO Pavement Design Guide[2] and are given in Table 5-2.

Table 5-1. Equivalent 18-KIP Load Applications per Truck

	Single Unit Trucks		Combination Trucks	
	Flexible Pavement	Rigid Pavement	Flexible Pavement	Rigid Pavement
Rural:				
Interstate	0.2898	0.4056	1.0504	1.6278
Other Principal Arterials	0.3141	0.4230	1.1034	1.7651
Minor Arterials	0.2291	0.3139	1.0205	1.0819
Collectors	0.2535	0.3485	0.7922	1.3265
Urban:				
Interstate and Other Freeways and Expressways	0.6047	0.8543	2.3517	3.7146
Other Principal Arterials	0.5726	0.8123	0.8584	1.3047
Minor Arterials	0.3344	0.4109	1.0433	1.5276
Collectors	0.8126	1.1595	0.6417	0.9968

Table 5-2. Lane Load Distribution Factors

Number of Lanes (One Direction)	Lane Factor
1	1.0
2	0.9
3	0.7
4 or more	0.6

HERS estimates pavement deterioration using Percent Average Daily Single Unit Commercial Vehicles and Percent Average Daily Combination Commercial Vehicles. HERS allows the user to specify a set of annual growth factors to be applied to each section's percent truck values. (See section 2.11 “The Fleet Composition Model” on page 2-15.)

For any time period beginning at t_0 and ending at t_f, HERS first calculates the total traffic:

2. American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, Washington, D.C., 1986.

$$TOTRAF = \frac{(AADT_{t_0} + AADT_{t_f})}{2} \times 365 \times (t_f \angle t_0) \qquad \textbf{Eq. 5.1}$$

where $(t_f \angle t_0)$ represents the length of the period in years.

HERS then calculates ESALs for the time period:

$$\begin{aligned} ESALS = {} & (TOTRAF \times PCAVSU \times ELF_{SU} \times LF) \\ & + (TOTRAF \times PCAVCM \times ELF_{CM} \times LF) \end{aligned} \qquad \textbf{Eq. 5.2}$$

where:

ESALS	=	ESALs accumulated during the time period;
PCAVSU	=	average percentage of single-unit trucks during the time period;
ELF_{SU}	=	equivalent load factor for single unit trucks for this pavement type and functional class (from Table 5-1);
PCAVCM	=	average percentage of combination trucks during the time period;
ELF_{CM}	=	equivalent load factor for combination trucks for this pavement type and functional class (from Table 5-1); and
LF	=	lane load distribution factor (from Table 5-2).

HERS uses one-half the length of a funding period as the time period for calculating total traffic and incremental ESALs in order to capture changes in both AADT and average percentages of trucks. Therefore, when estimating the number of ESALs which will accumulate during a funding period, it utilizes Equations 5.1 through 5.2 twice, once for the first half and once for the second half of the funding period.

5.1.2 Pavement Condition

HERS determines present and future pavement condition using the AASHTO 1993 guidelines. The first step is to obtain the number of ESALs that would have resulted in causing PSR to decline from 5.0 to its base-year value. The number of ESALs applied during any subsequent period is then estimated and added to the previous ESAL value. This result is then used to estimate PSR at the end of this period.

For flexible pavement, the HPMS database contains either the structural number (SN) or pavement weight (light, medium or heavy); for rigid pavement it contains either thickness (D) or pavement weight. If any of the optional information is not provided for a section, HERS uses the default values shown in Table 5-3 to obtain values describing the initial pavement. When the pavement is improved, procedures described in section 4.2.4 “Effects of HERS Improvements” on page 4-20 are used to obtain the thickness of the overlays or of the new pavement and, for flexible pavements, a new value of SN.

5.1.2.1 Flexible Pavement

For flexible pavements, the number of ESALs that would cause PSR to decline from 5.0 to its base-year value is obtained using the equation:

$$ESAL = 10^{LOGELA} \qquad \textbf{Eq. 5.3}$$

Table 5-3. Pavement Section Default Values

	Pavement Section		
	Heavy	Medium	Light
SN (Flexible Pavement)	5.3	3.8	2.3
D (Rigid Pavement)	10.0	8.0	6.5

where:

$$LOGELA = XA + XG/XB + X0 + XM \qquad \textbf{\textit{Eq. 5.4}}$$

$$XA = 9.36 \times \log(SNA) \angle 0.2 \qquad \textbf{\textit{Eq. 5.5}}$$

$$XB = 0.4 + 1094/SNA^{5.19} \qquad \textbf{\textit{Eq. 5.6}}$$

$$XG = \log((5 \angle PSRI)/3.5) \qquad \textbf{\textit{Eq. 5.7}}$$

$$SNA = SN + \sqrt{(6/SN)} \qquad \textbf{\textit{Eq. 5.8}}$$

$$X0 = ZR \times S0 \qquad \textbf{\textit{Eq. 5.9}}$$

$$XM = 2.32 \times \log(MR) \angle 8.07 \qquad \textbf{\textit{Eq. 5.10}}$$

$$ZR = ANORIN(REL) \qquad \textbf{\textit{Eq. 5.11}}$$

and

PSRI	=	PSR at the beginning of the base year;
ANORIN	=	name of the function that evaluates the inverse of the standard normal (Gaussian) distribution function;
S0, *REL*, *MR*	=	input parameters taken from Table 5-4;

and all logarithms are taken to the base ten.

Table 5-4. Flexible Pavement Input Parameters

Input Parameter	Description	Varies By	Default Values	
S0	Prediction error	Pavement type	0.49 0.39	Flexible Rigid
REL	Reliability Factor	Functional Class	90% 85% 80%	Interstates Other Arterials Collectors
MR	Modulus of Resistance	Functional Class	4000 for all FC's	

The PSR at the end of any subsequent time period, *PSRF*, is then obtained by adding the number of ESALs incurred during that time period to the initial value of ESALs, substituting *PSRF* for *PSRI* in Equation 5.7, solving the above system of equations for

PSRF, and performing the indicated computations. Solving Equation 5.7 for *PSRF* produces:

$$PSRF = 5 \angle 3.5 \times PDRAF_{pt} \times 10^{XG} \qquad \textbf{Eq. 5.12}$$

where:

$PDRAF_{pt}$	=	A user-specified pavement deterioration rate adjustment factor for pavement type *pt*, normally set to one[3];

and solving Equation 5.3 and Equation 5.4 for XG produces:

$$XG = XB \times (\log(ESALTF) \angle XA \angle X0 \angle XM) \qquad \textbf{Eq. 5.13}$$

where *ESALTF* is the total number of ESALs accumulated at the time of interest.

5.1.2.2 Rigid Pavement

The procedure for obtaining the pavement condition of rigid pavements follows the same approach as that for flexible pavements: it also is based upon Equation 5.3. But for rigid pavements, LOGELA is defined:

$$LOGELA = X0 + XA + XG/XB + XN \times XC \qquad \textbf{Eq. 5.14}$$

where:

$$XA = 7.35 \times \log(D + 1) \angle 0.06 \qquad \textbf{Eq. 5.15}$$

$$XB = 1 + 16.24 \times 10^{6}/(D + 1)^{8.46} \qquad \textbf{Eq. 5.16}$$

$$XN = 4.22 \angle 0.32 \times PT \qquad \textbf{Eq. 5.17}$$

$$XC = \log\left\{\frac{SCP \times CD \times (D^{0.75} \angle 1.132)}{215.63 \times J \times (D^{0.75} \angle 18.42/(EC/K)^{0.25})}\right\} \qquad \textbf{Eq. 5.18}$$

and

X0	=	as per flexible pavement in Equation 5.9;
XG	=	as per flexible pavement in Equation 5.7;
D	=	pavement thickness;

and PT, SCP, CD, J, EC, and K are input parameters as shown in Table 5-5 .

For rigid pavement, the solution for *XG* (the analogue to Equation 5.13) becomes:

$$XG = XB \times (\log(ESALTF) \angle XA \angle X0 \angle XN \times XC) \qquad \textbf{Eq. 5.19}$$

and HERS uses Equation 5.12 to solve for *PSRF*, the PSR at the time of interest.

3. If HERS is being used to analyze data for a single state, $PDRAF_{pt}$ can be used to reflect the effects of the state's environment and materials used in that state. Separate values of $PDRAF_{pt}$ can be specified for flexible and rigid pavement types.

Table 5-5. Rigid Pavement Input Parameters

Input Parameter	Description	Default Value
PT	Design terminal serviceability index	2.5
SCP	Modulus of rupture	600
CD	Load transfer coefficient	1
J	Drainage coefficient	3.0
EC	Modulus of elasticity	3.5×10^6
K	Modulus of subgrade reaction	200

5.1.2.3 Minimum Deterioration Rate

For both flexible and rigid pavements, minimum deterioration rates are used to reflect pavement deterioration due to environmental conditions. HERS uses the following equation to calculate an appropriate minimum deterioration rate:

$$PSRMAX_t = PSR_{t_0} \times ((PDL)/(NPSRAI))^{((t \angle t_0)/ML)} \qquad \textbf{\textit{Eq. 5.20}}$$

where:

t	=	any time of interest;
$PSRMAX_t$	=	upper limit on the PSR of a given section at time t;
t_0	=	time at which the section was last improved or, if not known, six months before the beginning of the HERS run;
PDL	=	pavement deficiency level;
NPSRAI	=	"normal" PSR after improvement; and
ML	=	maximum life of the section in years from Table 5-6.

The use of Equation 5.20 requires knowing the time that each section was last improved (t_0) and the PSR immediately after the improvement (PSR_{t0}). For all improvements analyzed or selected by HERS, this information is readily available. For improvements that occurred prior to the start of a HERS run, the preprocessor uses the time of last improvement specified in the HPMS dataset, if available, or the middle of the year preceding the start of the HERS run. If the preprocessor finds that the section's initial PSR is greater than the maximum PSR on that section after resurfacing, the time of improvement t_0 is set to six months before the beginning of the analysis period and the initial PSR is used as the PSR after improvement *NPSRAI.* Otherwise, the preprocessor uses the maximum permissible PSR after resurfacing.

The maximum pavement life values for rigid and flexible pavements for three types of pavement section (light, medium and heavy) are shown in Table 5-6.

Table 5-6. Maximum Pavement Life Values (Years)

Surface Type	Pavement Section		
	Heavy	Medium	Light
Flexible	25	20	15
Rigid	30	25	20

The HERS model then enforces the minimum deterioration rate:

$$PSRMX_t = \text{the lesser of} \begin{cases} PSRMAX_t \\ PSR_{t_{ESALS}} \end{cases} \qquad \textbf{\textit{Eq. 5.21}}$$

where:

$PSRMAX_t$	=	upper limit on PSR at time *t* from Equation 5.20;
PSR_{tESALS}	=	PSR at time *t* as a function of ESALs (PSRF from Equation 5.12); and
$PSRMX_t$	=	PSR at time *t* after enforcement of the minimum deterioration rate.

5.1.2.4 Maximum Deterioration Rate

A user-specified maximum PSR deterioration rate is used to limit pavement deterioration on sections with low values of SN. The default value for this maximum rate of deterioration is 0.3 per year. This maximum rate is applied after the enforcement of the minimum deterioration rate:

$$PSR_t = \text{the larger of} \begin{cases} PSR_{t_0} \angle MAXPDR \times (t \angle t_0) \\ PSRMX_t \end{cases} \qquad \textbf{\textit{Eq. 5.22}}$$

where:

t	=	any time of interest;
PSR_t	=	PSR at the time *t* after enforcement of both the maximum and minimum deterioration rates;
t_0	=	time at which the section was last improved or, if not known, six months before the beginning of the HERS run;
$PSRMX_t$	=	PSR at time *t* after enforcement of the minimum deterioration rate from Equation 5.21; and
$MAXPDR$	=	maximum PSR deterioration rate per year.

5.1.2.5 Minimum PSR Level

Having forecast the future PSR based upon ESALs, and then applied limitations based upon minimum and maximum pavement deterioration rates, HERS applies a minimum PSR level below which no section is permitted to deteriorate. The minimum level is defined by *PSRUPS*, the PSR value for unpaved sections. The user specifies *PSRUPS* as a control input to HERSPP (see paragraph 3.2.1, ”The Preprocessor Control Inputs”). The supplied *PSRUPS* value is 1.0.

5.2 Estimating Operating Costs

The cost of operating a vehicle on a given section is a function of costs for fuel, oil, tires, maintenance and repair, and mileage-related depreciation. This section discusses the method by which HERS estimates operating costs. These estimates exclude the effect of taxes.[4]

HERS treats operating costs as having three sources, and derives its estimates using a three-step procedure:

1. Constant-speed operating costs are estimated as a function of average effective speed, average grade, and PSR;
2. Excess operating costs due to speed-change cycles are estimated; and
3. Excess operating costs due to curves are estimated.

Figure 5-1 provides an overview of the operating cost calculations.

The operating cost calculation process, as outlined above and detailed in the paragraphs below, is performed for each of the seven vehicle types. For the two truck categories the process is performed once for each direction unless free-flow speed and uphill free-flow speed are the same (see section 5.4.1 "Free-Flow Speed and the APLVM" on page 5-33). The process is performed only once for four-wheel vehicles, as HERS assumes that grades do not affect free-flow speed for these vehicles.

5.2.1 Operating Cost Components

HERS recognizes five components of operating costs:

- fuel consumption
- oil consumption
- tire wear
- maintenance and repair
- depreciable value.

All five components are included in the calculation of constant-speed costs and excess costs due to speed change cycles: for excess costs due to curves, only fuel, tire wear, and maintenance and repair are included.

5.2.1.1 Component Prices

Table 5-7 shows estimates of component prices in 1997 dollars for use in estimating operating costs. The sources of these estimates are described below.

Fuel prices for two-axle vehicles were derived by subtracting federal and state gasoline taxes[5] from the 1997 retail price of gasoline, and fuel prices for larger vehicles

4. From the standpoint of the user, taxes are part of user costs. However, from the standpoint of the overall economy, taxes are transfer payments that entail no resource costs.
5. U. S. Department of Transportation, Federal HIghway Administration, *Highway Statistics, 1997*, Washington, D.C., 1998, Table MF-121T.

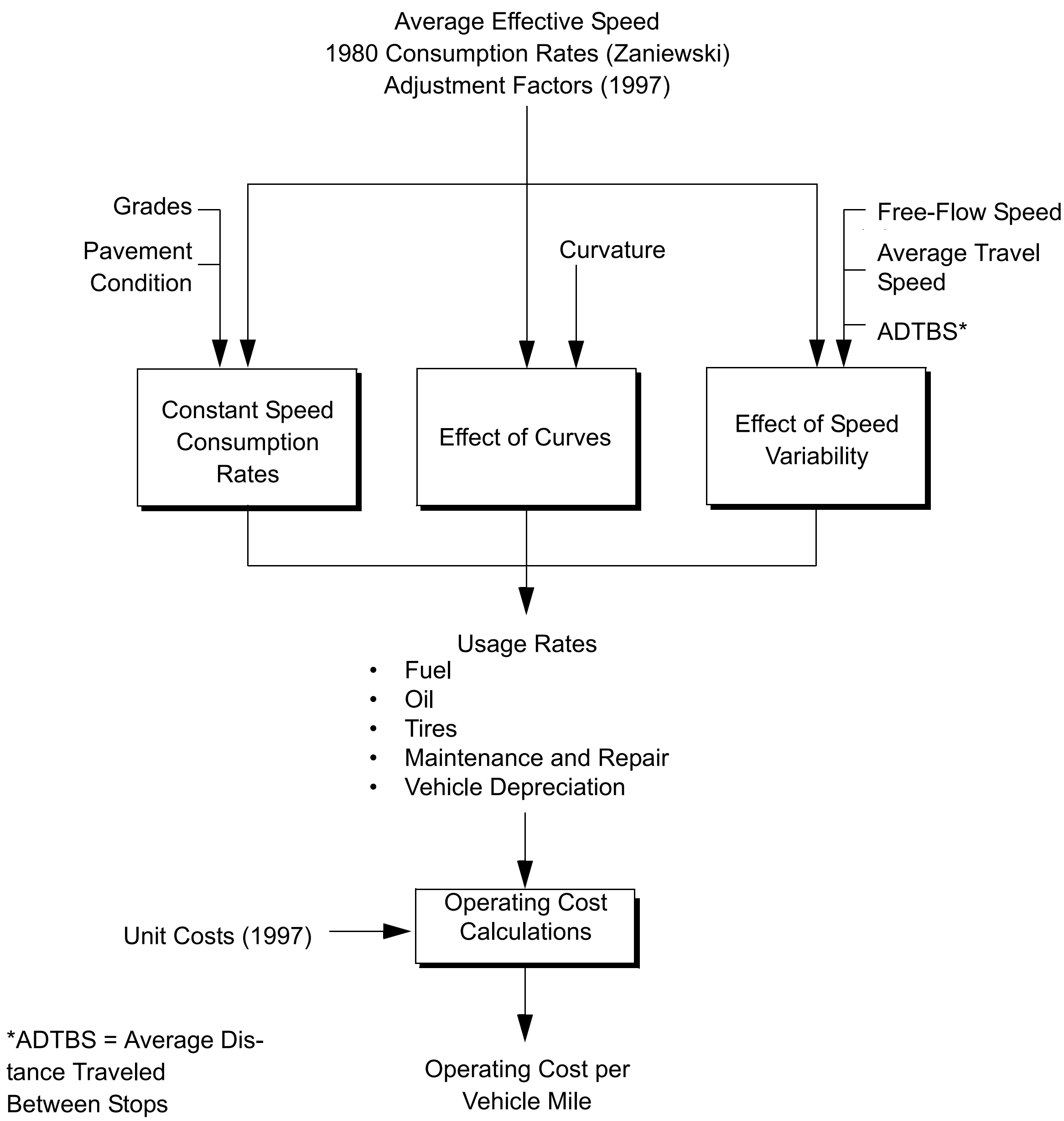

Figure 5-1. Operating Cost Calculation Flow

were derived by subtracting taxes on diesel fuel from the average 1997 retail price of highway diesel fuel.[6]

6. U.S. Department of Energy, Energy Information Administration, "On-Highway Diesel Fuel Price Survey," Form EIA-888, 1995.

Table 5-7. Component Prices (1997 dollars)

Vehicle Type	Fuel ($/gallon)	Oil ($/quart)[a]	Tires ($/tire)	Maintenance and Repair ($/1,000 miles)	Depreciable Value ($/vehicle)
Automobiles					
Small	$0.871	$3.573	$45.2	$84.1	$18,117
Medium/Large	0.871	3.573	71.5	102.1	21,369
Trucks					
Single Units					
4 Tires	0.871	3.573	78.8	129.8	23,028
6 Tires	0.871	1.429	190.1	242.9	34,410
3+ Axles	0.762	1.429	470.7	343.5	75,702
Combination					
3-4 Axles	0.762	1.429	470.7	355.8	87,690
5+ Axles	0.762	1.429	470.7	355.8	95,349

a. The unit cost for oil includes the labor charge for changing the oil.

Values for the cost of oil and tires were obtained by applying appropriate price indexes to the 1995 estimates previously developed[7] from the original Zaniewski estimates[8]. The price index used for oil is the consumer price index (CPI)[9] for motor oil, coolant, and fluids (SS47021). Tire costs were indexed using the CPI for tires (SETC01). The tire-cost index reflects the effects of improvements in quality (as downward adjustments in the index) - improvements that generally decrease the rate of tire wear. Maintenance and repair costs were indexed using the CPI for motor vehicle maintenance and repair (SETD).

For medium and heavy trucks, following Zaniewski, depreciable value was obtained by subtracting tire costs from the vehicle's retail price and then subtracting ten percent salvage value. For the three heaviest vehicles, the vehicle prices were those used by the recent Federal Highway Cost Allocation Study[10] (for three-axle dump trucks and for combinations with a tandem-axle van semi-trailer). The retail price of a 1995 28,000 pound gross vehicle weight six-tire truck was obtained from the Truck Blue Book[11] and adjusted to include a van body.

For the two classes of automobiles, 1995 depreciable value was obtained by adjusting the 1993 values[12] for changes in the average price paid for a new car.[13] For four-tire

7. Cambridge Systematics, Inc., *Revisions to HERS*, prepared for the Federal Highway Administration, December 1997, Chapter 7.
8. J.P. Zaniewski, *et.al.*, *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*, Texas Research and Development Foundation, prepared for U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1982, Table 2, p. 7.
9. U.S. Department of Labor, Bureau of Labor Statistics, Consumer Price Index Database.
10. U. S. Department of Transportation, FHWA, *1997 Federal Highway Cost Allocation Study*, August 1997.
11. Maclean Hunter Market Reports, *Truck Blue Book*, Chicago, January 1995.
12. Cambridge Systematics, Inc., *op. cit*. The 1993 values were derived from the original Zaniewski values using the same procedure.

trucks, 1995 depreciable value was obtained judgementally from the 1995 value for medium/large automobiles by comparing the range of list prices of minivans and sport-utility vehicles to the range for medium and large automobiles.[14] For all vehicle classes, 1997 depreciable value was then obtained by applying the change in the average price of a new car between 1995 and 1997.

5.2.1.2 Adjustment Factors for Consumption Rates

The parameters used by the operating cost equations have been indexed to reflect reductions in fuel and oil consumption rates and depreciation rates that occurred between 1980 and 2000. Increases in tire durability are reflected in the consumer and producer price indexes (which have increased by only a few percent since 1980), so separate adjustments are not needed for changes in the rate of tire wear. Similarly, no adjustments were made in the amount of maintenance required; reductions in the requirements for routine maintenance are reflected in the data used for adjusting maintenance costs per mile through 1995[15] (but not in the BLS data used for the 1995-2000 adjustment).

The adjustments for changes in fuel efficiency, oil consumption, and vehicle depreciation are discussed below.

5.2.1.2.1 Fuel Efficiency Adjustment Factor

The fuel efficiency adjustment factors for automobiles and four-tire trucks were obtained by dividing on-road fuel efficiency for the 2000 fleet of automobiles and light trucks by corresponding 1980 values. The 1980 values were obtained from Energy and Environmental Analysis.[16] The 2000 values were developed using the following data from the *Transportation Energy Data Book* published annually by Oak Ridge National Laboratory (ORNL):[17]

- 1976-2000 sales of automobiles and 1970-2000 sales of light trucks
- 1976-2000 EPA fuel efficiencies by vehicle class
- estimated survival rates.

The surviving fleets of pre-1970 light trucks and pre-1976 automobiles were assumed to be three times the number of surviving 1970 light trucks and 1976 automobiles, respectively. Fuel efficiencies of pre-1976 automobiles were estimated by extrapolation, while fuel efficiencies of pre-1976 light trucks were assumed to be the same as those of 1976 light trucks (which are 11 percent below those of 1977 light trucks). All

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13. U.S. Department of Commerce, Bureau of Economic Analysis, "Average Transaction Price of a New Car," quoted in American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996*, Detroit, 1996, page 60. This source provides a better indication of changes in vehicle prices than the appropriate components of the CPI and PPI, because the latter indexes are adjusted (downward) to exclude the effect on prices of improvements in the quality of new vehicles. On the other hand, none of the adjustments reflect the effects that some of these improvements have had on servicing requirements or depreciation rates (which, ideally, should be handled by modifying the operating cost equations for maintenance and repair).
14. The alternative approach of adjusting the original Zaniewski values using data on changes in the price of a new car was rejected because it does not adequately reflect the increase in the quality of appointments of four-tire trucks that has occurred during the last several years. The rejected procedure produces a 1995 value of only $17,002 (instead of the $20,742 value actually used).
15. Runzheimer International, quoted in American Automobile Manufacturers Association, Motor Vehicle Facts and Figures, 1996, Detroit, 1996, p. 58.
16. Energy and Environmental Analysis, Inc., *The Motor Fuel Consumption Model: Thirteenth Periodical Report*, prepared for the U.S. Department of Energy, Washington, D.C., January 1988, page B-1.
17. Oak Ridge National Laboratory, *Transportation Energy Data Book*, various editions.

averaging was performed using fuel consumption rates (gallons per mile); and in-use fuel efficiency was assumed to be 15 percent below the EPA value.

A single 20-year fuel-efficiency adjustment factor for the three classes of heavy trucks was developed by obtaining the ratio of the 1997 and 1977 fuel-efficiency estimates for in use Class 8 trucks developed by ORNL using data from the Truck Inventory and Use Survey (TIUS). The relatively modest increase in fuel efficiency (39.6 percent over 20 years) is due, in part, to increases in vehicle weights.

The fuel efficiency adjustment factor for six-tire trucks was similarly developed from TIUS data using a weighted average of fuel efficiency estimates for Class 6 trucks (19,500 to 26,000 pound gross vehicle weight). Class 6 is the largest of the five truck classes (Classes 3-7) that consist primarily of six-tire trucks. Use of data for a single truck class minimizes the effect of changes in the mix of six-tire vehicles occurring over the period.

The resulting fuel efficiency adjustment factors are shown in Table 5-8.

Table 5-8. Fuel Efficiency Adjustment Factors (2000 Factors)

Vehicle Type	Factor
Small Automobiles	1.550
Medium/Large Automobiles	1.550
4-Tire Trucks	1.666
6-Tire Trucks	1.344
3+ Axle Trucks	1.396
3-4 Axle Combinations	1.396
5+ Axle Combinations	1.396

5.2.1.2.2 Oil Consumption Adjustment Factor

The most common recommended oil-change interval for new automobiles was 7,500 miles in both 1980 and 2000. However, for various reasons, some slight reduction in oil consumption between these two years was likely. (These reasons include a reduction in the number of older cars with shorter oil-change intervals and reduced burning of oil.) Accordingly, an oil-consumption reduction factor of 1.05 was assumed for all vehicle classes.

5.2.1.2.3 Depreciation Rate Adjustment Factor

The average age of the automobile fleet increased from 6.6 years in 1980 to 8.6 years in 1996.[18] Extrapolating to 2000, we estimate average age to be 9.1 years, suggesting a 38 percent increase in longevity (or a decline in the average rate of depreciation of about 28 percent). The same increase in average longevity was assumed for trucks.

18. R. L. Polk and Company, as quoted in American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996*, Detroit, 1996, p. 39.

5.2.2 Constant-Speed Operating Costs

For each vehicle type (vt), constant-speed operating cost per thousand vehicle-miles (*CSOPCST*) is estimated as the sum of five cost components representing costs for fuel, oil, tires, maintenance and repair, and vehicle depreciation. The overall equation for combining these components is:

$$\begin{aligned} CSOPCST_{vt} = {} & CSFC \times PCAFFC \times COSTF_{vt} / FEAF_{vt} \\ & + CSOC \times PCAFOC \times COSTO_{vt} / OCAF_{vt} \\ & + 0.01 \times CSTW \times PCAFTW \times COSTT_{vt} / TWAF_{vt} \\ & + 0.01 \times CSMR \times PCAFMR \times COSTMR_{vt} / MRAF_{vt} \\ & + 0.01 \times CSVD \times PCAFVD \times COSTV_{vt} / VDAF_{vt} \end{aligned} \qquad \textbf{Eq. 5.23}$$

where:

$CSOPCST_{vt}$	=	constant speed operating cost for vehicle type *vt;*
$CSFC$	=	constant speed fuel consumption rate (gallons/ 1000 miles);
$CSOC$	=	constant speed oil consumption rate (quarts/1000 miles);
$CSTW$	=	constant speed tire wear rate (% worn/1000 miles);
$CSMR$	=	constant speed maintenance and repair rate (% of average cost/1000 miles);
$CSVD$	=	constant speed depreciation rate (% of new price/ 1000 miles);
$PCAFFC$	=	pavement condition adjustment factor for fuel consumption;
$PCAFOC$	=	pavement condition adjustment factor for oil consumption;
$PCAFTW$	=	pavement condition adjustment factor for tire wear;
$PCAFMR$	=	pavement condition adjustment factor for maintenance and repair;
$PCAFVD$	=	pavement condition adjustment factor for depreciation expenses;
$COSTF_{vt}$	=	unit cost of fuel for vehicle type *vt*;
$COSTO_{vt}$	=	unit cost of oil for vehicle type *vt*;
$COSTT_{vt}$	=	unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$	=	unit cost of maintenance and repair for vehicle type *vt*;
$COSTV_{vt}$	=	depreciable value for vehicle type *vt*;
$FEAF_{vt}$	=	fuel efficiency adjustment factor for vehicle type *vt*;
$OCAF_{vt}$	=	oil consumption adjustment factor for vehicle type *vt*;
$TWAF_{vt}$	=	tire wear adjustment factor for vehicle type *vt*;
$MRAF_{vt}$	=	maintenance and repair adjustment factor for vehicle type *vt*; and
$VDAF_{vt}$	=	depreciation adjustment factor for vehicle type *vt*.

Equations for estimating constant-speed consumption rates for fuel, oil, tires, maintenance and repair, and vehicle depreciation are shown in Appendix E, "Operating Cost

Equations." In these equations, *AES* is average effective speed in miles per hour (an output of the speed model), and *GR* is grade (in percent). The equations were estimated by applying ordinary least squares regression to the consumption tables presented in Zaniewski,[19] and have been modified to handle the higher speeds that HERS will encounter as a result of the recent increase in speed limits.

The Zaniewski tables represent estimated consumption rates for equipment in use in 1980 on roads with PSR = 3.5. Table E-16 on page E-11 presents equations for estimating pavement-condition adjustment factors for oil consumption, tire wear, maintenance and repair, and vehicle depreciation. These equations also were estimated by applying ordinary least squares regression to the adjustment factors presented in Zaniewski.[20]

Zaniewski does not provide pavement-condition adjustment factors for fuel consumption. Accordingly, the corresponding adjustment factor used for HERS is set to one. However, the factor has been included in the code for symmetry and to allow development of such a factor in the future.

5.2.3 The Effect of Speed-Change Cycles

HERS calculates excess operating costs due to speed-change cycles (or speed variability) for sections which have stop signs or traffic signals. The overall formula for calculating these costs is similar to that for constant speed operating costs (see Equation 5.23) with two exceptions: the consumption rates are derived from a different set of equations, and no pavement condition adjustment factors are used. For each vehicle type (*vt*), excess operating costs per thousand vehicle-miles due to speed variability (*VSOPCST*) is estimated:

$$\begin{aligned} VSOPCST_{vt} = {} & VSFC \times COSTF_{vt}/FEAF_{vt} \\ & + VSOC \times COSTO_{vt}/OCAF_{vt} \\ & + VSTW \times COSTT_{vt}/TWAF_{vt} \\ & + VSMR \times COSTMR_{vt}/MRAF_{vt} \\ & + VSVD \times COSTV_{vt}/VDAF_{vt} \end{aligned} \qquad \textbf{Eq. 5.24}$$

where:

$VSOPCST_{vt}$	=	excess operating cost due to speed variability for vehicle type *vt*;
VSFC	=	excess fuel consumption rate due to speed variability (gallons/1000 miles);
VSOC	=	excess oil consumption rate due to speed variability (quarts/1000 miles);
VSTW	=	excess speed tire wear rate due to speed variability (% worn/1000 miles);
VSMR	=	excess speed maintenance and repair rate due to speed variability (% of average cost/1000 miles);
VSVD	=	excess depreciation rate due to speed variability (% of new price/1000 miles);
$COSTF_{vt}$	=	unit cost of fuel for vehicle type *vt*;

19. *Op. cit*., Appendix B.
20. *Ibid*., Figure 5 and Tables 12, 15, and 19.

$COSTO_{vt}$	=	unit cost of oil for vehicle type *vt*;
$COSTT_{vt}$	=	unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$	=	unit cost of maintenance and repair for vehicle type *vt*;
$COSTV_{vt}$	=	depreciable value for vehicle type *vt*;
$FEAF_{vt}$	=	fuel efficiency adjustment factor for vehicle type *vt*;
$OCAF_{vt}$	=	oil efficiency adjustment factor for vehicle type *vt*;
$TWAF_{vt}$	=	tire wear efficiency adjustment factor for vehicle type *vt*;
$MRAF_{vt}$	=	maintenance and repair efficiency adjustment factor for vehicle type *vt*; and
$VDAF_{vt}$	=	depreciation adjustment factor for vehicle type *vt*.

These equations were also derived from Zaniewski, and are only applied to sections with stop signs or traffic signals. The equations are shown in Tables E-28 through E-91.

Signals and stop signs (as a group) are assumed to be uniformly spaced on each section. (This assumption is also used in the speed model.) Sections with both signals and stop signs are treated as having all signals at one end of the section and all stop signs at the other end. The two portions of the sections are analyzed separately, producing separate estimates of excess costs per 1000 cycles for the stop-sign and traffic signal portions of the section.

For each section, the estimates of excess costs per 1000 cycles are converted to excess costs per 1000 miles by dividing by the average distance between stops for stop signs and traffic signals. For traffic signals, this denominator reflects an adjustment for the probability of actually being stopped at a traffic signal. If both stop signs and traffic signals exist on the section, the sum of the excess costs for the two parts of the section is used.

5.2.4 The Effect of Curves

HERS uses the original Zaniewski tables[21] and equations derived from those tables for estimating excess operating costs due to curves. Two-dimensional linear interpolation of table values is used for sections with average effective speed below 55 m.p.h., and equations fit to the tables are used for sections with average effective speed above 55 m.p.h. On sections with zero degrees of curvature, excess costs are set to zero.

For medium and high speeds (generally above 40 m.p.h.), the Zaniewski values for excess costs due to curves with one degree of curvature are higher (and sometimes substantially higher) than those due to curves with two degrees of curvature. The values for one degree of curvature were deemed to be excessive and were ignored in estimating the equations for average effective speeds above 55 m.p.h. Similarly, the questionably high values for one degree of curvature were modified to more reasonable values in the tables used for sections with average effective speeds below 55 m.p.h.

21. *Ibid*., Appendix A, Tables A.73-A.80.

5.2.4.1 Sections With AES Below 55 M.P.H.

HERS uses the individual Zaniewski tables for the effects of curves on fuel consumption, tire wear, and maintenance and repair. (The effects of curves on vehicle depreciation and oil consumption were assumed to be negligible by Zaniewski.) During program initialization, the values in these tables are:

1. Multiplied by exogenously specified factors representing improvements since 1980 in fuel consumption, tire wear, and maintenance and repair;
2. Multiplied by exogenously specified unit prices; and
3. Summed.

The result is a single table of excess costs due to curves for each vehicle type (in dollars per 1000 vehicle miles) as a function of curvature and speed (up to 55 m.p.h.). For individual sections, excess costs due to curves for each vehicle type are estimated using average effective speed and curvature on the sections and using two-dimensional linear interpolation between entries in the table.

5.2.4.2 Sections with AES Above 55 M.P.H.

For sections with average effective speeds equal to or greater than 55 m.p.h., HERS uses equations fit to the Zaniewski values given for speeds of 55-70 m.p.h. and two degrees of curvature or more. Equations for use with sections having two or less degrees of curvature were devised to match the modified table values. Similar to the overall formula for constant-speed operating costs, HERS calculates the excess cost due to curves (*COPCST*) for each vehicle type on sections with average effective speed greater than 55 m.p.h.:

$$\begin{aligned} COPCST_{vt} = {} & CFC \times COSTF_{vt}/FEAF_{vt} \\ & + 0.01 \times CTW \times COSTT_{vt}/TWAF_{vt} \\ & + 0.01 \times CMR \times COSTMR_{ct}/MRAF_{vt} \end{aligned} \qquad \textbf{Eq. 5.25}$$

where:

$COPCST_{vt}$	=	excess operating cost due to curves for vehicle class *vt*;
CFC	=	excess fuel consumption rate due to curves (gallons/1000 miles);
CTW	=	excess tire wear rate due to curves (% worn/1000 miles);
CMR	=	excess maintenance and repair rate due to curves (% of average cost/1000 miles);
$COSTF_{vt}$	=	unit cost of fuel for vehicle type *vt*;
$COSTT_{vt}$	=	unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$	=	unit cost of maintenance and repair for vehicle type *vt*;
$FEAF_{vt}$	=	fuel efficiency adjustment factor for vehicle type *vt*;
$TWAF_{vt}$	=	tire wear adjustment factor for vehicle type *vt*; and
$MRAF_{vt}$	=	maintenance and repair adjustment factor for vehicle type *vt*.

The equations used to produce *CFC*, *CTW*, and *CMR* are shown in Tables E-40 through E-53.

5.2.5 Total Operating Costs

The HERS operating cost process is implemented as two nested loops. The outer loop propels the model through each vehicle type in turn. The inner loop is executed twice, once in each direction for each vehicle type. The calculation of the three categories of operating costs is performed within this inner loop. When operating costs in both directions for all vehicle types have been calculated, the model weights the costs using the procedures in section 2.11 "The Fleet Composition Model" on page 2-15 to arrive at the total operating cost per vehicle mile over the section.

5.3 Safety Costs

The HERS safety analysis is a three-step procedure:

1. Estimate numbers of crashes using separate procedures for each of six facility types;
2. Apply functional-class-specific injury/crash ratios and fatality/crash ratios to estimate numbers of injuries and fatalities; and
3. Multiply by appropriate cost parameters to produce estimates of the total cost of crashes.

The procedures for estimating the number of crashes are described and documented in the next paragraph. The subsequent section, 5.3.2, "Fatalities and Injuries," presents the injury/crash ratios and fatality/crash ratios. Section 5.3.3, "Secular Trends," develops estimates, for use by HERS, of the extent to which recent secular declines in crash rates, fatality/crash ratios, and injury/crash ratios are due to factors not analyzed by HERS. In section 5.3.4, "Costs of Crashes," data from a recent report by the National Highway Traffic Safety Administration (NHTSA) is used to update HERS' estimates of costs per injury and property damage costs per crash, as well as to provide estimates of the cost of travel-time delay per crash.

5.3.1 Crash Rates

HERS estimates the numbers of crashes and crash rates using separate procedures for three types of rural facility and three types of urban facility. The facility types distinguished are:

- freeways (by design);
- multi-lane roads and streets; and
- two-lane roads and streets.

The freeway procedures are used for all divided roads[22] with four or more lanes and full access control, and also for all one-way roads with two or more lanes and full access control. These procedures are used for these roads regardless of functional system. For all other facilities with four or more lanes and all other one-way facilities with two or three lanes, the "multi-lane" procedures are used, again regardless of functional system. Finally, the "two-lane" procedures are used for all two-way facilities with fewer than four lanes and for all one-lane facilities.

Five of the procedures are slightly modified versions of procedures recommended by Richard Margiotta based on an extensive review of the literature.[23] The sixth procedure is derived from the results of an analysis by Vogt and Bared[24] that was performed after the completion of Margiotta's work.

All procedures were modified to produce estimates of crash rates per 100 million vehicle-miles of travel (VMT) and calibrated to crash-rate data for 1995. The six procedures (after calibration) are described in sections 5.3.1.1 through 5.3.1.6, and the calibration is described in section 5.3.1.7.

5.3.1.1 Rural Two-Lane Roads

The procedure for estimating crashes on rural two-lane roads develops separate estimates of crashes within 250 feet of an intersection and crashes on segments between intersections. Both sets of estimates are developed using equations based on those developed by Vogt and Bared.[25] These estimates are then combined:

$$CRASH = 1.056 \times (CNINT + CINT) \qquad \textbf{\textit{Eq. 5.26}}$$

where

CRASH	=	total number of crashes on the section per 100 million VMT;
CNINT	=	non-intersection crashes per 100 million VMT;
CINT	=	crashes occurring within 250 feet of an intersection, per 100 million VMT on the section;

and 1.056 is the calibration factor developed in section section 5.3.1.7 "Calibration" on page 5-26. The procedures for estimating *CNINT* and *CINT* are presented below.

5.3.1.1.1 Non-intersection Crashes

The equation for estimating non-intersection crashes is based on an equation developed by Vogt and Bared using Highway Safety Information System (HSIS) data for Minnesota and Washington.[26] The HERS equation is:

22. For the purpose of the safety analysis, a divided road has a positive barrier median or a median width of at least four feet. This definition is slightly narrower than the HPMS definition of a divided (FHWA, *Highway Performance Monitoring System Field Manual*, Appendix I, pp. I-1 and I-8, January 1998). The HPMS definition, which is used by the HERS capacity procedures, also classifies roads with curbed medians of any width as being divided. Because narrow curbed medians provide relatively limited protection from median crossing, our safety procedure treats roads with curbed medians and median widths of less than four feet as being undivided.
23. Richard Margiotta, *Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process*, prepared by COMSIS Corporation and Science Applications International Corporation for FHWA, September 1996, Chapter 2.
24. Andrew Vogt and Joe Bared, "Accident Models for Two-Lane Rural Segments and Intersections," presented at the TRB Annual Meeting, January 1998.
25. Ibid.
26. *Ibid.*, p. 6. Vogt and Bared also use the data from Minnesota and Washington separately to develop two additional equations for non-intersection crashes (p. 5).

$$CNINT = 100 \times ADJSL / SLEN \qquad \textbf{\textit{Eq. 5.27}}$$

$$\times \exp(0.72 \angle 0.085 \times LW \angle 0.059 \times SHW + 0.067 \times RHR + 0.0085 \times DD$$

$$+ 0.44 \times CCGR)$$

$$\times \left(\sum_i LCURV_i \times \exp(0.045 \times CURV_i) \right) / SLEN$$

$$\times \left(\sum_i LGRD_i \times \exp(0.011 \times GRD_i) \right) / SLEN$$

where

SLEN	=	section length (in miles);
ADJSL	=	section length adjusted to exclude segments within 250 feet of an intersection;
LW	=	lane width (in feet);
SHW	=	shoulder width (in feet);
RHR	=	roadside hazard rating (3.0);
DD	=	driveway density (per mile) (3.7 for rural type of development, 50 for dense development);
$CURV_i$	=	average degrees of curvature in HPMS curve class *i*;
$LCURV_i$	=	total length (in miles) of all curves in curve class *i*;
GRD_i	=	average percent grade in HPMS grade class *i*;
$LGRD_i$	=	total length (in miles) of all grades in grade class *i*; and
CCGR	=	crest curve grade rate in percent per hundred feet (zero for flat terrain, 0.03 for hilly terrain, and for mountainous terrain).

In Equation 5.27, HERS uses the factor of 100 to convert the estimate of crashes from being expressed per million VMT (as in Vogt and Bared) to being expressed per 100 million VMT in HERS.

The ADJSL/SLEN factor adjusts the estimate of non-intersection crashes to reflect only travel that occurs more than 250 feet from an intersection. (The procedure treats crashes occurring within 250 feet of an intersection as intersection crashes.) For this purpose, *ADJSL* is obtained from *SLEN* by subtracting 500/5,280 times the number of intersections; if the result is negative, *ADJSL* is set to zero. This adjustment enables the HERS procedure to avoid producing unreasonably high estimates of total crashes for sections with moderate to high numbers of intersections per mile.[27]

Vogt and Bared use a dummy variable, *STATE*, to distinguish between Minnesota and Washington data. In Equation 5.27, *STATE* has been set to 0.5 (effectively weighting data from both states equally), and the term corresponding to *STATE* has been combined with the constant term to produce a modified constant term (0.72).

The value used in Equation 5.27 for the roadside hazard rating (*RHR*) is 3.0, which approximates the average value for all sections used in the Vogt and Bared analysis.

The values used for driveway density (*DD*) are assumed to vary by type of development. For rural development, driveway density should be somewhat below the median for rural types of development, and for dense development it should be appreciably higher. The median values in the data used by Vogt and Bared are 3.73 for Minnesota and 6.12 for Washington; the means are 6.58 and 10.12, respectively; and the maxima are 85.1 and 100, respectively. This data suggests that it is appropriate to set *DD* to 3.7 where development is rural and to set it to 50 where development is dense. When these values are used with 1995 HPMS data, the VMT-weighted average value of DD is 8.29, just slightly below 8.35, the unweighted average of the means for Minnesota and Washington. (The value of 50 for dense development implies an average of 211 feet between driveways.)

The values for crest curve grade rate (*CCGR*) were also based on a judgmental review of Vogt and Bared data. In their data, the median values for this variable were 0.024 in Washington and 0.037 in Minnesota, suggesting that 0.03 is a reasonably typical value for hilly terrain. Similarly, the maximum value was 2.0 in Washington (and 0.89 in Minnesota). Since most crests can be assumed to have *CCGR* values that are appreciably below the maximum, a typical value of 0.4 was assumed for mountainous terrain. Finally, for flat terrain, *CCGR* values are likely to be zero or close to zero; accordingly, a value of zero was used.

Finally, if necessary, the HPMS-coded lengths of curves ($LCURV_i$) are scaled so that their sum equals the coded section length (*SLEN*); and, if necessary, a corresponding adjustment is made to the lengths of the grades ($LGRD_i$).[28]

5.3.1.1.2 Intersection Crashes

Vogt and Bared used HSIS data for Minnesota to develop separate equations for estimating crashes at three-legged intersections and crashes at four-legged intersections. The HPMS database does not distinguish between three and four-legged intersections, but it does distinguish between:

1. Intersections with traffic signals;
2. Intersections with stop signs on the sample section; and
3. All other intersections.

To avoid double-counting, HERS assigns all crashes at the second type of intersection to the intersecting road and all crashes at the third type to the sample section. A portion of crashes at intersections with traffic signals are assigned to the sample section using assumptions presented subsequently.

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27. Vogt and Bared did not incorporate an *ADJSL/SLEN* adjustment in their analysis. The inclusion of this adjustment in the HERS equation would, by itself, reduce HERS' estimate of total crashes on rural two-lane roads. However, since the HERS estimates are calibrated to 1995 data, the actual effect of the adjustment is to increase the size of the calibration factor (1.056 in Equation 5.26), leaving the estimate of total crashes unchanged but shifting some crashes from sections with high numbers of intersections per mile to sections with lower numbers of intersections per mile.
28. The adjustments are made in the HERS preprocessor and are applied to all sections for which curves or grades are coded. (Previously, adjustments were made when the total length of curves (or grades) exceeded coded section length but not when they were less than coded section length.)

HERS treats all signalized intersections as four-legged intersections. “Other” intersections (i.e., Type 3 intersections) are treated as a mix of three- and four-legged intersections by using a weighted average of the two Vogt and Bared equations. The weights used are 0.55 for three-legged intersections and 0.45 for four-legged intersections.[29] Since all crashes at intersections with stop signs are assigned to the intersecting road, crashes at these intersections are not estimated.

With the above assumptions, estimates of the number of crashes at intersections are obtained from the following equations:

$$CINT = \frac{10^8}{VMT} \times (CSINT + COINT4 + COINT3) \qquad \textbf{Eq. 5.28}$$

$$\begin{aligned} CSINT = {} & 0.2 \times NSIG \times FSICAS \\ & \times \exp(\angle 7.74 + 0.64 \times \ln(ADT1) + 0.58 \times \ln(ADT2) \\ & + 0.33 \times CCGR \angle 0.053 \times ADJIA + 0.11 \times ND) \end{aligned} \qquad \textbf{Eq. 5.29}$$

$$\begin{aligned} COINT4 = {} & 0.2 \times 0.45 \times NOINT \\ & \times \exp(\angle 7.74 + 0.64 \times \ln(AADT) + 0.58 \times \ln(ADT2) \\ & + 0.33 \times CCGR \angle 0.053 \times ADJIA + 0.11 \times ND) \end{aligned} \qquad \textbf{Eq. 5.30}$$

$$\begin{aligned} COINT3 = {} & 0.2 \times 0.55 \times NOINT \\ & \times \exp(\angle 11.48 + 0.82 \times \ln(AADT) + 0.51 \times \ln(ADT2) \\ & + 0.26 \times CCGR + 0.036 \times DC + 0.027 \times SPDLIM \\ & + 0.18 \times RHR3LI + 0.24 \times PRTL) \end{aligned} \qquad \textbf{Eq. 5.31}$$

where *CINT* and *CCGR*[30] have been defined above and the other variables are:

VMT	=	vehicle miles traveled on the section in one year;
CSINT	=	annual crashes at signalized intersections;
COINT4	=	annual crashes at “other” four-legged intersections (i.e., intersections with neither signals nor stop signs on the sample section);
COINT3	=	annual crashes at “other” three-legged intersections;
NSIG	=	number of signalized intersections;
FSICAS	=	*AADT/(ADT1+ADT2)* = fraction of total *AADT* on the inventoried section;
ADT1	=	at signalized intersections, *AADT* on the road with the higher traffic volume;
ADT2	=	at any intersection, *AADT* on the road with the lower traffic volume;
ADJIA	=	“adjusted intersection angle” (2.0);
NOINT	=	number of “other” intersections;
AADT	=	Annual Average Daily Traffic;
ND	=	number of driveways within 250 feet of a given intersection = (500/5,280) x *DD*;

29. The database used by Vogt and Bared contained data for 389 three-legged intersections and 327 four-legged intersections. The weights used were obtained by reducing the latter figure by an estimate of the number of signalized intersections (based on 1995 HPMS data), all of which are treated as four-legged intersections by the HERS procedure.
30. We considered the possibility that crest curve grade rate and average curvature would have lower values in the vicinity of an intersection than they would have for the section as a whole. However, this hypothesis was not supported by the data in Vogt and Bared.

DC	=	average degrees of curvature on the section;[31]
SPDLIM	=	speed limit (mph);
RHR3LI	=	roadside hazard rating for three-legged intersections (2.1); and
PRTL	=	probability that a three-legged intersection has a right-turn lane (0.42).

In the case of signalized intersections, *AADT* on intersecting roads is assumed to vary with the functional class of the road section being analyzed. In the case of principal arterials, the intersecting road is assumed to carry less traffic than the section in question, so *ADT1* is set to *AADT* and *ADT2* is assumed equal to one-half *AADT*. In the case of major collectors, the reverse is assumed, so *ADT2* is set to *AADT* and *ADT1* is assumed equal to twice *AADT*. For minor arterials, traffic volumes on both roads are assumed (on average) to be equal, so *ADT1* and *ADT2* are both set to *AADT*.

Crashes at signalized intersections are allocated to the inventoried section and to the intersecting roads in proportion to their relative traffic volumes. Thus, *FSICAS* (fraction of signalized-intersection crashes attributed to the inventoried section) is two-thirds for principal arterials, one-half for minor arterials, and one-third for major collectors.

"Other" intersections are unsignalized intersections which do not have stop signs on the inventoried section. These sections are assumed to have stop signs on the intersecting roads and relatively low volumes on these roads. For these intersections *ADT2* is assumed to be the lesser of 500 and one-half *AADT*. All crashes at these intersections are allocated to the inventoried section (and all crashes at intersections with stop signs on the inventoried section are allocated to the intersecting roads).

If the total number of intersections (signalized, stop sign, and "other") exceeds 20 per mile, the number of each type of intersection is scaled so that the total is reduced to 20 per mile and the scaled-down numbers are used for *NSIG* and *NOINT* in the above equations (and also for deriving *ADJSL* for use in Equation 5.27).

Vogt and Bared define "adjusted intersection angle" (*ADJIA*) to be $(\alpha - 15)^2/100$, where α is the departure of the intersection angle from 90°, measured in degrees. This variable equals 2.25 when $\alpha = 0°$ or 30°, equals zero when $\alpha = 15°$, is below 2.0 when α is between 1° and 29°, and exceeds 2.25 when $\alpha > 30°$. The Vogt and Bared data for α suggests that 2.0 is a reasonable average value for *ADJIA*.

Vogt and Bared assigned roadside hazard ratings of one to seven for conditions on the main road within 250 feet of an intersection. The average value of these ratings for three-legged intersections, 2.1, has been adopted as the default value for the corresponding variable (*RHR3LI*) in Equation 5.31. Similarly, the default value of 0.42 assumed for the probability that a three-legged intersection has a right-turn lane (*PRTL*) represents the fraction of such intersections with right-turn lanes in the data used by Vogt and Bared.

The factor 0.2 in Equations 5.29 through 5.31 is used to transform the corresponding Vogt and Bared equations, which estimate intersection crashes over a five-year period, into equations that produce estimates of the expected numbers of annual crashes.

31. See preceding footnote.

5.3.1.2 Rural Multilane Roads

The equation for estimating the number of crashes per 100 million vehicle-miles on rural multilane roads is:

$$\begin{aligned} CRASH = {} & 132.2 \times AADT^{0.073} \\ & \times \exp(0.131 \times RHRRML - 0.151 \times AC + 0.034 \times DDRML \\ & + 0.078 \times INTSPM - 0.572 \times RPA + 0.0082 \times (12 - LW) \\ & - 0.094 \times SHLDW - 0.003 \times MEDW + 0.429 \times (DEVEL - 1)) \end{aligned} \qquad \textbf{\textit{Eq. 5.32}}$$

where:

RHRRML	=	roadside hazard rating for rural multilane roads (2.45);
AC	=	1 for sections with (full or partial) access control,
	=	0 for other sections;
DDRML	=	driveway density (per mile) for rural multilane roads (0.41 for rural type of development, 5.6 for dense development);
INTSPM	=	intersections per mile (maximum =10);
RPA	=	1 for rural principal arterials and rural Interstate,
	=	0 for lower functional systems;
LW	=	lane width, in feet (between 8 and 13 feet);
SHLDW	=	right shoulder width, in feet (maximum = 12 feet);
MEDW	=	50 if positive barrier median,
	=	median width, in feet, otherwise (maximum = 50); and
DEVEL	=	type of development (1 for rural, 2 for dense).

Equation 5.32 is a modified version of an equation for estimating crashes on rural highways that was fit to Minnesota HSIS data for rural four-lane roads by Wang, Hughes and Stewart.[32] The following modifications were made to the estimated equation:

- The equation has been divided by 365 times daily VMT and multiplied by 100 million in order to produce estimates of crashes per 100 million vehicle-miles instead of annual crashes.
- The coefficient (132.2) is the product of the coefficient from the original equation (0.0002), the above adjustment factor (273,973), and a calibration coefficient (2.4123, see section 5.3.1.7 "Calibration" on page 5-26).
- A factor, (section length)$^{0.073}$, has been dropped from the equation since there does not appear to be any reason for crash rates to vary with section length.
- Signalized intersections (which were excluded from the original analysis) have been assumed to have the same influence on crash rates as unsignalized intersections (though this assumption may actually underestimate their influence).
- For want of HPMS data on turn lanes for rural sections, the original equation's distinction between intersections with turn lanes and those without turn lanes has been dropped and the two terms combined.[33]

32. Jun Wang, Warren Hughes and Richard Stewart, *Safety Effects of Cross-Section Design of Rural Four-Lane Highways*, FHWA Report FHWA-RD-98-071, May 1998, Equation 6.

- The value, 2.45, used for roadside hazard rating (RHRRML) approximates the average value of the ratings used by Wang, Hughes and Stewart.
- Values used for driveway density were obtained by multiplying the corresponding values used for rural two-lane roads by 0.112 (0.112 is the approximate ratio of driveway density on two-lane rural roads in Minnesota used by Bared and Vogt to the driveway density on four-lane roads in Minnesota used by Wang, Hughes and Stewart).
- Lane width (which was found not to be a significant variable in the original analysis[34]) has been assumed to have one-tenth as much influence as it has for rural two-lane roads (cf. Equation 5.27); this assumption appears to be more realistic than assuming that crash rates are totally unaffected by lane width.
- Maximum values of 12 feet for right shoulder width and 50 feet for median width have been assumed, as recommended by Margiotta;[35] increases in shoulder and median widths beyond these values are likely to have appreciably smaller effects on crash rates than would be indicated by the exponential form of Equation 5.32.
- A maximum value of ten has been assumed for INTSPM (intersections per mile). A summary of data used in the original analysis indicates it is unlikely that any of the sections analyzed in deriving Equation 5.32 had more than ten intersections per mile.[36] The equation is relatively sensitive to INTSPM: a value of ten multiplies the result by 2.2; a value of 20 would multiply the result by 4.8.[37]
- A barrier median is assumed to have the same effect on crash rates as a 50-foot median. (Only one of the sections originally studied had a barrier median, so this effect could not be analyzed.)
- The HPMS and HERS variable “type of development” (rural dense or rural rural) is assumed to be a reasonable proxy for the “area location type” variable (rural municipal or rural non-municipal) used in the original analysis, though the match may be imperfect. (“Rural municipal” may include some small urban places that would be coded as “urban” by HPMS and HERS, and it may exclude some small rural developments that would be coded as “rural dense” by HPMS and HERS.)

5.3.1.3 Rural Freeways

The equation for estimating the number of crashes per 100 million vehicle-miles on rural freeways is:

$$CRASH = 17.64 \times AADT^{0.155} \times \exp(0.0082 \times (12 \angle LW)) \qquad \textbf{\textit{Eq. 5.33}}$$

This equation incorporates a lane-width factor into an equation originally developed by Persaud[38] for four-lane freeways and calibrated to HPMS data for all rural free-

33. The coefficient (0.078) of the combined term was obtained as a weighted average of the original coefficients, using data from Wang, Hughes and Stewart to obtain weights representing the approximate number of intersections with turn lanes per mile (0.22) and the approximate number of intersections without turn lanes per mile (0.74).
34. The variable actually used by Wang, Hughes and Stewart was width of road surface.
35. *Op. cit.*, Figure 2.9.
36. Wang, Hughes and Stewart, *op. cit.*, Table 2.
37. The current HPMS database has a moderate number of sections with 20 or more intersections per mile.
38. B. N. Persaud, *Roadway Safety: A Review of the Ontario Experience and of Relevant Work Elsewhere*, prepared for the Ministry of Transportation, Ontario, 1992.

ways. The effect of lane width (*LW*) is assumed to be the same as that assumed for other rural multilane roads. The variables used by this equation have been defined previously.

Persaud's equation actually estimates crashes per mile per year. Equation 5.33 was derived from Persaud's equation by multiplying by section length, dividing by annual VMT (equal to 365×AADT×section length), multiplying by 108, and multiplying by the estimated calibration factor (0.8442).

Persaud also derived a separate equation for rural freeways with more than four lanes. However, for any value of AADT, the equation for freeways with more than four lanes produces appreciably higher crash rates than the equation for freeways with four lanes, implying that crash rates vary inversely with congestion. This result is inconsistent with those of most other analyses.[39, 40]

5.3.1.4 Urban Freeways

The equation for estimating the number of crashes per 100 million vehicle-miles on urban freeways is:

$$CRASH = (154.0 \angle 1.203 \times ACR + 0.258 \times ACR^2 \angle 0.00000524 \times ACR^5) \times \exp(0.0082 \times (12 \angle LW)) \qquad \textbf{Eq. 5.34}$$

where ACR = AADT divided by two-way hourly capacity and the other variables have been defined previously. This equation incorporates a lane-width factor into an equation developed by Margiotta[41] using results from Tedesco, *et. al.*,[42] and Margiotta and Cohen.[43] The effect of lane width is assumed to be the same as that assumed for rural multilane roads.

5.3.1.5 Urban Multilane Surface Streets

The equation for estimating the number of crashes on urban multilane surface streets and on urban expressways lacking full access control is:

$$CRASH = A \times AADT^B \times NSIGPM^C \qquad \textbf{Eq. 5.35}$$

where:

A, B, and *C*	=	values from Table 5-9; and
NSIGPM	=	number of signals per mile.

The value of NSIGPM, the number of signals per mile, has a minimum value of 0.1 and a maximum value of eight. This equation was derived from an equation for estimating annual crashes per mile that was estimated by Margiotta[44] using data from

39. See B. Persaud and L. Dzbik, "Accident Prediction Models for Freeways," *Transportation Research Record* 1401, 1993.
40. For low values of AADT (less than 24,000), crash rates were also found to be higher on freeways with more than four lanes in FHWA's *Highway User Investment Study* (as reported in *HPMS Analytical Process*, Volume II, Technical Manual, 1987, page IV-41 and Appendix J). However, this result is of little significance since very few freeways with such low values of AADT have more than four lanes. To enable HERS and the AP to avoid assuming that adding lanes to four-lane freeways will increase crashes, Margiotta recommended that only Persaud's equation for four-lane freeways be used.
41. Richard Margiotta, *op. cit.*, pp.15-19, 25 and 28.
42. Shelby A. Tedesco, *et. al.*, "Development of a Safety Model to Assess the Impact of Implementing IVHS User Services," *Proceedings of the IVHS America 1994 Annual Meeting*, April 1994.
43. Richard Margiotta and Harry Cohen, *Roadway Usage Patterns: Urban Case Studies*, prepared by Science Applications International Corporation and Cambridge Systematics for Volpe National Transportation Systems Center, June 1994.

Bowman and Vecellio.[45] The derivation involved multiplying Margiotta's equations by section length, dividing by annual VMT, multiplying by 108, and incorporating calibration factors. The upper and lower limits on the number of signals per mile were recommended by Margiotta.

Table 5-9. Parameters for Crash-Rate Equation for Urban Multilane Surface Streets

Type of Section	A	B	C
Two-Way with Left-Turn Lane	95.1	0.1498	0.4011
One-Way, or Two-Way with a median: 1) wider than 4 feet, or 2) curbed, or 3) a "positive barrier"	82.6	0.1749	0.2515
Otherwise	115.8	0.1749	0.2515

5.3.1.6 Urban Two-Lane Streets

For two- and three-lane urban streets, crashes are estimated using the equation:

$$CRASH = \angle 19.6 \times \ln(AADT) + 7.93 \times (\ln(AADT))^2 \qquad \textbf{\textit{Eq. 5.36}}$$

This equation was developed by using ordinary least squares regression to fit a function of this form to the data shown in Table 5-10 and multiplying by the calibration factor in Table 5-11. The r^2 for this regression is 0.99.

Table 5-10. Data Used for Estimating Crash Rates for Urban Two-Lane Streets

AADT Range	Mean Value of AADT Within Range[a]	Crashes per 100 Million VMT[b]
< 4,000	1,978	345
4,000 - 7,999	5,739	490
8,000 - 15,999	11,101	590
> 15,999	20,417	660

a. Weighted average mean value obtained from the 1995 HPMS database for streets to which the "two-lane urban streets" procedure is applied (i.e., all one-lane urban streets and two-way urban streets with two or three lanes).

b. Crash rates used in original HERS safety procedure.

5.3.1.7 Calibration

The crash-rate equations were calibrated in two steps.

44. *Op. cit.*, pp. 19-22, 25 and 29.
45. Brian L. Bowman and Robert L. Vecellio, "Effect of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety," Transportation Research Record 1445, 1994, pp. 169-179. This source actually provided data only for roads with raised medians, roads with two-way left-turn lanes, and other undivided roads. (Roads with two-way left-turn lanes are considered to be divided roads in the safety literature and are treated as such in this report; however, they are classified as undivided in the HERS and HPMS capacity analyses.)

In the first step, the equations used by the six procedures presented above were calibrated separately to crash rates for the corresponding highway types. These rates were obtained by Margiotta[46] as a VMT-weighted average of rates developed by Zegeer and Williams[47] using data for four states from the HSIS. The rates used are shown in the first column of Table 5-11.

Table 5-11. Crash Rates Used for Calibration[a]

Facility	Crashes per 100 million VMT	Calibration Factor
Rural		
Freeway	68.0	0.8842
Multilane	146.6	2.4123
Two Lane	163.8	1.0557
Urban		
Freeway	131.0	1.1453
Multilane		
Divided	439.1	
Median		0.9367
Two-Way Left-Turn Lane		0.7494
Undivided	554.8	1.3131
Two-Lane	378.7	0.8743

a. Derived from rates developed using Highway Safety Information System data for Illinois, Maine, Minnesota and Utah. Separate rates were developed for each state by C.V. Zegeer and C. Williams (*Calculation of Accident Rates by Roadway Class for HSIS Status*, University of North Carolina Highway Research Center, June 1994). The above rates are VMT-weighted averages of these rates developed (using 1994 HPMS data) by Richard Margiotta (*Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process*, prepared by COMSIS Corporation and Science Applications International Corporation for FHWA, September 1996, Table 2.3).

In the second step, the six calibration factors were scaled uniformly to produce an overall rate of 309.7 crashes per 100 million VMT. This rate was obtained by multiplying an estimate of total crashes in 1995 from the National Highway Traffic Safety Administration's General Estimates System (GES)[48] by an undercapture correction factor of 1.12[49] and dividing by national VMT in that year.[50] [51] The calibration factors produced by this two-step procedure are shown in the right column of Table 5-11.

46. Margiotta, *op. cit.*, pp. 7-8.
47. C.V. Zegeer and C. Williams, *Calculation of Accident Rates by Roadway Class for HSIS States*, University of North Carolina Highway Research Center, June 1994. The four states used were Illinois, Maine, Minnesota and Utah. This source contains crash rates for five states. However, rates for the fifth state, Michigan, are appreciably higher than those for the other four states (for rural areas, they are, on average, twice as high). Accordingly, Michigan data were excluded from our calibration.
48. National Highway Traffic Safety Administration, *Traffic Safety Facts - 1996*, Table 1.
49. Lawrence J. Blincoe and Barbara M. Faigin, *The Economic Cost of Motor Vehicle Crashes, 1990*, NHTSA, Report DOT HS 807 876, 1992, as quoted in Ted R. Miller, Diane C. Lestina and Rebecca S. Spicer, "Highway Crash Costs in the United States by Driver, Age, Blood Alcohol Level, Victim Age, and Restraint Use," *Accident Analysis and Prevention*, Vol. 30, No. 2, 1998.
50. FHWA, Highway Statistics - 1995, Table VM-1.

These factors are included in Equations 5.26 through 5.36 as presented in sections 5.3.1.1 through 5.3.1.6.

The calibration factor for urban two-lane streets results from the replacement of the step function previously used by a continuous function and from a decline in crash rates between 1988 and 1995. (The step function was last calibrated using 1988 data.) The calibration factors for urban multilane streets incorporate separate calibration factors developed by Margiotta[52] for the three types of multilane streets distinguished.

The other calibration factors generally represent differences, that are not explained by any of the independent variables, between the crash rates observed in the data used in developing the original equations and the HSIS and national crash rates used in the calibration process. The high calibration factor for rural multilane roads is due to very low average crash rates in the HSIS data used by Wang, Hughes and Stewart in their analysis of crash rates on rural multilane roads. The factor for rural two-lane roads incorporates an upward adjustment to counter the effect of the ADJSL/SLEN factor that we added to Equation 5.27 (see section 5.3.1.1.1 "Non-intersection Crashes" on page 5-18).

5.3.2 Fatalities and Injuries

The HERS safety procedure estimates fatalities and nonfatal injuries as being directly proportional to the number of crashes, with separate ratios used for each functional system. The ratios were obtained by:

- taking estimates of fatality and crash rates per 100 million vehicle-miles by functional system for 1995;[53] and
- dividing by corresponding estimates of the number of crashes per 100 million vehicle-miles by functional system produced by the new HERS procedure for estimating numbers of crashes described in the preceding chapter.[54]

The resulting ratios are shown in Table 5-12.

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51. No adjustment was made for differences in overall crash rates between the nine functional systems covered by HPMS sample-section data and the three systems (rural minor arterials and the two local systems) that are not covered. To the extent that crash rates on the latter systems may be lower than average, our calibration procedure may result in a slight upward bias in the HERS estimates of crashes on the nine systems covered by HERS. Since the other three systems account for only 15 percent of national VMT, the effect of this bias should be fairly small.
52. *Op. cit.*, pp. 25 and 29.
53. FHWA, *Highway Statistics, 1995,* Table FI-1.
54. An alternate approach for obtaining ratios by highway type (instead of by functional system) was also investigated. This approach used a calibration process that was more complicated than the one finally adopted, along with HSIS data on numbers of crashes, fatalities and injuries by highway type in six states, and corresponding estimates of 1995 VMT obtained from HPMS sample-section data. However, the HSIS estimates of the numbers of crashes on rural multilane roads (and, in particular, undivided rural multilane roads) in these states were found to be inconsistent with the corresponding HPMS estimates of VMT in these states, making it impractical to calibrate the equations appropriately.

Table 5-12. Fatality and Injury Rates

Functional System	Fatalities per Crash	Injuries per Crash
Rural		
Interstate	0.01408	0.4546
Other Principal Arterial	0.01685	0.6317
Minor Arterial	0.01362	0.5610
Major Collector	0.01370	0.6261
Urban		
Interstate	0.00382	0.4908
Other Freeway or Expressway	0.00396	0.3640
Other Principal Arterial	0.00273	0.4113
Minor Arterial	0.00237	0.3401
Collector	0.00257	0.3496

5.3.3 Secular Trends

Over time, the rates of injuries and fatalities in highway crashes have shown steady declines. In the past twenty years, fatalities per 100 million vehicle-miles have declined at an average annual rate of about four percent, and nonfatal injuries have declined at an average rate of about 2.25 percent.[55] Although highway improvements have contributed to this decline, several other factors have been major contributors. These include improvements in: vehicle designs; emergency medical care; and driver behavior (including reductions in drunk driving).

In order to allow HERS to incorporate the effects of these secular trends into its forecasts of crashes and crash costs, the safety model allows the user to specify annual percentage declines in:

- the rate of crashes per 100 million vehicle-miles;
- the ratio of injuries to crashes; and
- the ratio of fatalities to crashes.

Estimates of annual crashes for 1988 and subsequent years are available from NHTSA's General Estimates System (GES).[56] These values, when combined with FHWA's estimates of annual fatalities and nonfatal injuries,[57] indicate that, over the 1988-1995 period, the average annual rates of decline have been 1.0 percent for the ratio of (nonfatal) injuries to crashes and 1.3 percent for the ratio of fatalities to crashes, and the rates of decline since 1990 have been appreciably higher. Since the ratios developed in section 5.3.2 are for 1995, the decline in these ratios is assumed to

55. Derived from FHWA, *Highway Statistics Summary to 1995*, July 1997, Tables FI-210 and FI-220.
56. National Highway Traffic Safety Administration, *Traffic Safety Facts – 1996,* Table 1.
57. FHWA, *op. cit.* Estimates of 1996 fatalities and injuries (from Highway Statistics, Table FI-1) were excluded from this analysis because of inconsistencies between the FI-1 data and the FI-210 and FI-220 data. The latter data is currently being revised.

begin in 1996. The year of the data used for calibrating the fatality and injury ratios (currently 1995) is provided to HERS as a parameter and should be changed by the user whenever these ratios are changed.

Obtaining a forecast rate of decline to be applied to crash rates presents a somewhat greater problem. Combining the GES estimates of annual crashes since 1988 with FHWA estimates of annual VMT[58] produces estimates of crashes per 100 million vehicle-miles that drop from 340 in 1988 to 266 in 1993, rise more slowly to 277 in 1995, and decline very slightly to 276 in 1996. The average annual rate of decline between 1988 and 1995 (the time period used for estimating the decline rates for the fatality and injury ratios) is 2.6 percent, but a focus on more recent data would produce an appreciably lower annual rate of decline (and an *increase* if only data since 1993 is used[59]).

As the above discussion implies, data for the last few years suggests that there may be some weakening in the long-term trends toward reductions in crash, fatality and injury rates. It is not yet clear whether this weakening represents a temporary or permanent change in the secular rates of decline in the crash, fatality and injury rates. In preparing data for the 1999 Conditions and Performance Report, the rate of decline was set to zero (no decline).

5.3.4 Costs of Crashes

The HERS safety model estimates crash costs as the sum of the value of lives lost and the costs of injuries, property damage, and delay to other highway users. The value of lives lost is estimated by multiplying fatalities by the U.S. Department of Transportation's estimate of the value of life (currently $2.7 million). Unit costs for estimating the three other components of crash costs have been derived in large part from information contained in a recent National Highway Traffic Safety Administration (NHTSA) study of crash costs in 1994.[60]

5.3.4.1 Unit Costs of Crashes in 1994

HERS' estimates of injury costs are derived from estimates of comprehensive costs per injury developed by Ted Miller in 1991[61] and updated to 1994 dollars by NHTSA.[62] These estimates, which are based on the willingness-to-pay concept used by HERS, are provided by the Maximum Abbreviated Injury Scale (MAIS).[63] They

58. *Ibid.*, Table FI-200; and FHWA, *Highway Statistics, 1996, Table VM-1.*
59. In another test, the new HERS crash-estimation procedures were applied without a temporal adjustment to 1993 and 1996 HPMS data for 42 states. The procedures indicate a 0.6 percent increase in crash rates over this three-year period, apparently because of increased congestion. (All six procedures produce estimated crash rates that vary with AADT or AADT per lane.) However, the increase produced by the HERS procedures is appreciably lower than the 3.7 percent increase indicated for this three-year period by the GES and FHWA data.
60. Lawrence J. Blincoe, *The Economic Cost of Motor Vehicle Crashes, 1994*, NHTSA, 1996.
61. Ted R. Miller, *et. al.*, *The Costs of Highway Crashes*, The Urban Institute, 1991.
62. Blincoe, *op. cit.*, Table A-1. These estimates of comprehensive costs, based on willingness to pay, are, on average, roughly three times the NHTSA estimates of economic or "human capital" costs summarized in Table 1 of the Blincoe report.
63. An alternative to using costs by MAIS is the use of costs by police-reported "KABCO" code (killed; A, B or C injury; property damage only). Estimates of comprehensive costs by KABCO code are available in Ted R. Miller, Diane C. Lestia, and Rebecca S. Spicer, "Highway Crash Costs in the United States by Driver Age, Blood Alcohol Level, Victim Age, and Restraint Use," *Accident Analysis and Prevention*, Vol. 30, No. 2, 1998. However, these estimates probably should not be used with crash data from small numbers of states, since the source observes that KABCO coding varies appreciably across states.

range from \$10,840 for MAIS Level 1 to \$2,509,310 for MAIS Level 5 (and \$2,854,500 for fatal injuries). Weighting the estimates for nonfatal injuries by the relative frequency of injuries of each severity[64] produces an overall estimate of \$47,657 per police-reported injury.

Corresponding estimates of property-damage costs per crash and travel-delay costs per crash were obtained by dividing the NHTSA estimates of total 1994 costs of these two types[65] by an estimate of crashes in 1994 that is consistent with the 1995 estimate used to calibrate the HERS crash-estimation procedures.[66] This step produced overall costs-per-crash estimates of \$7,164 for property damage and \$605 for travel delay.

The next series of steps in the development of unit cost factors for use by the HERS safety model involved using the above overall estimates of unit costs for injuries and property damage to develop estimates by functional system. This was accomplished by:

1. Using the new HERS procedures and 1994 HPMS data to estimate crashes, injuries and fatalities by functional system in 1994;
2. Using unindexed values of HERS' original 1988 estimates of unit costs of injuries and property damage by functional system to obtain national estimates of unit costs implied by the original unit costs; and
3. Dividing the new estimates (in 1994 dollars) by those produced using 1988 unit costs.

This last step produced scale factors of 3.1062 for injury costs and 1.2532 for property damage costs. These scale factors were then applied to the 1988 HERS estimates of unit costs by functional system to produce a revised set of unit costs for injuries and property damage. The revised unit costs are shown in Table 5-13.

Delay costs vary with AADT per lane. HERS uses the equation:

$$DELCC = \frac{0.0886 \times AADT}{LANES} \times CRASH \qquad \textbf{\textit{Eq. 5.37}}$$

where

DELCC	=	cost of delay due to crashes (per 100 million VMT);
CRASH	=	crash rate on the section (per 100 million VMT); and
LANES	=	number of lanes.

The coefficient (0.0886) was set so that, when applied to 1994 data, HERS would produce an overall average cost of delay that matches the above estimate of \$605 per crash.

The assumption that the delay cost of crashes is linear with a simple measure of traffic volume (AADT per lane) undoubtedly understates the complexity of this relationship.

64. Blincoe, *op. cit.*, Table 3.
65. *Ibid.*, Table 1.
66. The resulting estimate of 1994 crashes, 7.28 million, was obtained by applying an undercapture correction factor of 1.12 (see section 5.3.1.7) to the NHTSA GES estimate of crashes in 1994.

Table 5-13. Injury and Property-Damage Costs

Functional System	Injury Cost per Injury (1994 dollars)	Property-Damage Costs per Crash (1994 dollars)
Rural		
Interstate	$52,800	$5,000
Other Principal Arterial	68,300	6,300
Minor Arterial	55,900	6,300
Major Collector	77,650	6,300
Urban		
Interstate	55,900	6,300
Other Freeway or Expressway	46,600	7,500
Other Principal Arterial	49,700	7,500
Minor Arterial	40,400	7,500
Collector	31,100	6,300

Hence, this simple procedure is likely to underestimate the delay cost of crashes on congested roads and to overestimate this cost on uncongested roads.

For sections with stop signs and for free-flow sections with only one lane in one or both directions, the delay cost of crashes is multiplied by the average value of an hour of travel time to estimate hours of delay due to crashes. For these sections, this value is used as an estimate of incident delay. For other sections, DELCC is no longer used by HERS.

5.3.4.2 Indexing the Costs of Crashes

HERS allows the costs of property damage, delay and injuries to be indexed from 1994 dollars to dollars of a subsequent year using separate, user-supplied index values. For property-damage costs, an appropriate index to use is the Consumer Price Index (CPI) component for automobile body work.[67] Using 1994 as a base year, the 1997 value of this index is 1.126, so property-damage costs per crash in 1997 are estimated as being 12.6 percent higher than in 1994.

For travel delay, the index used should be the same one as is used for the value of time, but the base year for the travel delay index would be 1994 (instead of 1995, the year currently used for value of time). The index currently being used for this purpose is the U.S. Bureau of Labor Statistics (BLS) Employment Cost Index (which reflects total compensation of all civilian workers).[68] Using 1994 as a base year, the 1997 value of this index is 1.089.

Injury costs have previously been indexed by HERS using the CPI component for medical care. However, since the HERS estimates of the comprehensive costs of injuries are based on willingness to pay, rather than on economic costs (which include

67. U.S. Bureau of Labor Statistics, Consumer Price Index – All Urban Consumers, Series ID CUUR0000SETD01, Motor Vehicle Body Work, http://stats.bls.gov/sahome.html (U.S. city average, not seasonally adjusted).
68. U.S. Bureau of Labor Statistics, Employment Cost Index, Series ID: ECS10001I, Total Compensation of All Civilian Workers, http://stats.bls.gov/sahome.html (seasonally adjusted).

medical costs), the cost of medical care may not be the most appropriate basis for indexing injury costs. A measure of perceived wealth or earnings ability is probably a better indicator of changes in willingness to pay. For simplicity, HERS uses the BLS Employment Cost Index for this purpose (as well as for indexing the cost of delay); therefore the 1997 value of this index is also 1.089.

5.4 The HERS Speed Model

HERS uses computed vehicle speed for three purposes: calculation of travel time costs; calculation of external costs due to vehicular emissions; and calculation of vehicle operating costs[69]. Average effective speed (AES) across the section is used in the first two calculations above and for most of the operating cost calculations. To calculate excess operating costs due to speed change cycles induced by traffic signals and/or stop signs, HERS uses distance travelled between traffic control devices and the average travel speed over the portions of the section which contain signals and stop signs.

Previously, the HERS speed model was based on the Texas Research and Development Foundation (TRDF) adaptation[70] of the "Aggregate Probabilistic Limiting Velocity Model" (APLVM), one of four related procedures originally developed by the World Bank.[71] HERS now uses a simplified version of the APLVM procedures to calculate "free-flow" speed (FFS). It then applies algorithms developed by Science Applications International Corporation (SAIC) and Cambridge Systematics, Inc.[72] (CSI) for FHWA to incorporate the effects vehicle speed of grades (free-flow speed uphill, or FFSUP), traffic-control devices, and congestion on speed.

For each section, HERS models speed for each of the seven vehicle types (except for autos and pickup trucks) in each direction of travel. Overall average speed per section is aggregated from the speeds of the individual vehicle types. HERS uses vehicle speed data in calculating operating costs and travel time costs.

5.4.1 Free-Flow Speed and the APLVM

The HERS version of APLVM involves a four-step procedure; the first three of which involve the computation of three "limiting velocities." These limiting velocities rep-

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69. See Figure 2-3 "Prediction and calculation model linkages." on page 2-3.
70. G.C. Elkins, *et al*., *Estimating Vehicle Performance Measures*, Texas Research and Development Foundation, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., July 1987, pp. 128-177.
71. Thawat Watanatada, Ashok M. Dhareshwar and Paulo Roberto S. Rezende Lima, *Vehicle Speeds and Operating Costs*, The World Bank, Johns Hopkins University Press, Baltimore, 1987.
72. Cambridge Systematics, Inc., Harry Cohen, and Science Applications International Corp., Sketch Methods for Estimating Incident-Related Impacts, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 1998, Section 2.3.; Science Applications International Corporation and Cambridge Systematics, Inc., *Roadway Usage Patterns: Urban Case Studies*, prepared for Volpe National Transportations Systems Center and the Federal Highway Administration, June 1994, Appendix A; Science Applications International Corporation, *et al*., *Speed Determination Models for the Highway Performance Monitoring System*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, October 31, 1993; Cambridge Systematics, Inc., *Revisions to the HERS Speed and Operating-Cost Procedures*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, January 25, 1996, Section 2; Cambridge Systematics, Inc., 2000 Revisions to HERS, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., August 2002.

resent the approximate speeds that would be obtained should a single factor (e.g., pavement condition) limit speed to a value much lower than would otherwise be the case. The three limiting velocities[73] are:

VCURVE	=	maximum allowable speed on a curve;
VROUGH	=	maximum allowable ride-severity speed; and
VSPLIM	=	maximum speed resulting from speed limits.

The fourth step is to combine the three limiting velocities, using the APLVM, to determine the free-flow speed.

In APLVM, the dominant role in the determination of free-flow speed[74] is played by the smallest of the limiting velocities.[75] Each of the other limiting velocities are assumed to play some probabilistic role in influencing the speed of some drivers, but, except when they have values close to that of the lowest velocity, their influence on average free-flow speed tends to be negligible.

The following subsections describe the four steps of the HERS version of APLVM.

5.4.1.1 Calculating the Effect of Curves

In the World Bank procedure, the effect on speed attributed to the presence of curves is represented by *VCURVE*. The World Bank estimates *VCURVE*, in meters per second:

$$VCURVE = \sqrt{(FRATIO + SP) \times g \times RC} \qquad \textbf{Eq. 5.38}$$

where:

RC	=	radius of curvature (meters);
SP	=	superelevation; and
g	=	the force of gravity = 9.81 m/sec^2.

The remaining variable in Equation 5.38, *FRATIO*, known as the maximum perceived friction ratio, is the ratio of the lateral force on a horizontal curve to the normal force. TRDF derived values for *FRATIO* of 0.103 for combination trucks and 0.155 for automobiles; and they suggest the use of the 0.155 figure for single-unit trucks as well. HERS uses these values.

Replacing radius of curvature in Equation 5.38 by degrees of curvature (DC) and converting the equation to estimate *VCURVE* in miles per hour produces:

$$VCURVE = 292.5 \times \sqrt{(FRATIO + SP)/(DC)} \qquad \textbf{Eq. 5.39}$$

73. HERS 2.0 used four limiting velocities: VCURVE, VROUGH, VDRIVE, and VMISC. VDRIVE was a function of vehicle characteristics and average grade, which are handled in HERS through calculation of uphill free-flow speed. The fourth limiting velocity, VMISC, was a replacement for a factor called “desired speed” (VDESIR) by the World Bank and TRDF, and reflected the effects of speed limits, safety concerns, and congestion. In HERS, these factors are represented by VSPLIM and the congestion delay algorithms applied to free-flow speed.
74. The World Bank and TRDF use the term “steady-state speed,” or Vss, to refer to free-flow speed.
75. The original version of APLVM also uses a fifth limiting velocity, maximum allowable braking speed on downhill sections (VBRAKE). This limitation affects only heavy trucks and only on long, steep downhill sections (e.g., a five percent grade more than 10.5 miles long, or an eight percent grade more than three miles long). Since most HPMS sections are less than five miles long, there are likely to be only a handful of sections for which one would find braking speed to be a limiting factor (though, undoubtedly, some additional HPMS sections are part of longer descents for which braking speed is indeed a factor). Accordingly, TRDF's recommendation to exclude VBRAKE from the procedure has been adopted.

For all arterial sections except urban minor arterials, a weighted average value of degrees of curvature can be obtained from detailed data on curves by class contained in the HPMS database. For all collectors and for urban minor arterials, typical values of degrees of curvature are produced by existing HPMS software from horizontal alignment adequacy and type of terrain. (The HPMS submittal software is used in preparation of the HPMS database prior to HERS' processing the data.)

Although data on superelevation are not contained in the HPMS database, typical superelevation can be estimated from degrees of curvature using the equation:

$$SP = \begin{cases} 0.0 & \text{for} DC \le 1 \\ 0.1 & \text{for} DC \ge 10\text{, otherwise:} \\ 0.0318 + 0.0972 + \ln(DC) \angle 0.0317 \times DC + 0.007 \times DC \times \ln(DC) \end{cases} \qquad \textbf{\textit{Eq. 5.40}}$$

This equation was derived by regression from a table presented by Zaniewski[76], but fits so well ($R^2 = 0.9999$) as to suggest that it may be the equation that was used to generate the values in the table.

5.4.1.2 Estimating Velocity Limited by Pavement Roughness

The effect of pavement roughness on speed is represented by *VROUGH*. HERS uses PSR to measure pavement roughness. Descriptions of pavement characteristics corresponding to the various PSRs are presented in Table 3-20 on page 3-33.

A review of these descriptions indicates that pavement condition begins to become a limiting factor on high speed roads at approximately the boundary between the Good (3.0 to 4.0) and Fair (2.0 to 3.0) ratings, suggesting that *VROUGH* should play a minimal role in limiting speed when PSR greater than or equal to 3.0. Similarly, the descriptions suggest 52.5 mph as an appropriate value for *VROUGH* when PSR equals 2.0.

In order to avoid a speed of zero when PSR drops to zero (which can occur in HERS when funds are short), and to allow additional user control over the function used for *VROUGH*, HERS allows the user to specify *VROUGH* as a pair of line segments with different slopes meeting at a user-specified breakpoint, *PSRB*. These parameters are specified in the parameter file PARAMS.DAT.

Specifically, HERS uses the function below when the section's *PSR* is greater than the PSR breakpoint *PSRB*:

$$VROUGH = VR2 + VRSLOP \times (PSR \angle PSRB) \qquad \textbf{\textit{Eq. 5.41}}$$

HERS uses the following equation when *PSR* is less than or equal to the breakpoint *PSRB*:

$$VROUGH = VR1 + (VR2 \angle VR1) \times \frac{PSR}{PSRB} \qquad \textbf{\textit{Eq. 5.42}}$$

where:

76. J.P. Zaniewski, *et al.*, *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*, Texas Research and Development Foundation, prepared for U.S. Department of Transportation, Washington, D.C., March 1982, p. E-7.

*VR*1	=	value of *VROUGH* when *PSR* is zero;
*VR*2	=	value of *VROUGH* when *PSR* = *PSRB* (the breakpoint); and
VRSLOP	=	slope of the function when *PSR* > *PSRB*

The default values of the above parameters are:

PSRB	=	1.0
*VR*1	=	5 mph
*VR*2	=	20 mph
VRSLOP	=	32.5[77]

For PSR below 2.5, the default values produce intentionally lower estimates of speed than either the current AP procedure or that proposed by TRDF. For PSR = 1.5, they produce *VROUGH* = 36 mph, while TRDF's formula would produce values of 48 mph for automobiles and 44 mph for large trucks,[78] and the AP procedure would permit speeds of 49 mph. On the basis of the preceding discussion, 36 mph appears to be a more appropriate speed; however, users can choose different values for the four parameters if higher values of *VROUGH* are desired.

For purposes of deriving *VROUGH* for unpaved sections, HERS treats these sections as having a PSR of 1.0 (i.e., when *VR1*, *VR2* and *VRSLO*P are set to their default values, *VROUGH* for unpaved sections is 20 mph); the user may change this PSR value if desired.

For HERS, the same formula for *VROUGH* is used for all vehicle classes. Using Brazilian data, the World Bank study[79] obtained results that imply a very significant difference (about 30 mph) between the effects of roughness on automobiles and on combination trucks; and TRDF has proposed formulas that produce a much more modest difference (two to four mph). However, TRDF did not provide any recommended formulas for use with single-unit trucks.

5.4.1.3 Estimating Velocity Limited by Speed Limits

HERS represents the effect of speed limits on speed with *VSPLIM*. *VSPLIM* is assumed to be 10 or 15 kilometers per hour greater than the speed limit. Fifteen kmph is used for urban freeways by design and rural multilane roads with partial or full access control and a median which is either a positive barrier or has a width of at least 4 feet. Ten kmph is used for all other sections. These values correspond to 6.215 and 9.323 mph.

5.4.1.4 Determining Free-Flow Speed

The general formula for estimating free-flow speed, *FFS*, is:

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77. This represents a change from HERS v2, where the default value for VRSLOP was set at 20. The previous value produced a limiting velocity of 60 mph for a pavement of PSR 3.0 -- This change produces a limiting velocity of 85 mph when PSR is 3.0.
78. The TRDF formulas are:

$$VROUGH = \frac{1}{0.025 \angle 0.00275 PSR} \quad \text{for automobiles}$$

$$VROUGH = \frac{0.9}{0.0255 \angle 0.00333 PSR} \quad \text{for large trucks}$$

79. Elkins, *et al.*, *op. cit.*, pp. 144-149.

$$FFS = \frac{\exp(\sigma^2/2)}{\left((1/VCURVE)^{\frac{1}{\beta}} + (1/VROUGH)^{\frac{1}{\beta}} + (1/VSPLIM)^{\frac{1}{\beta}}\right)^{\beta}} \qquad \textit{Eq. 5.43}$$

where σ^2 and β are parameters discussed below.

In the above equation, β is a parameter that may vary with vehicle class and reflects the standard deviation of the sensitivity of drivers of vehicles in that class to the different conditions reflected in the equation. For the moment, ignore the effect of σ^2 (i.e., assume $\sigma^2 = 0$). In this case, when two factors produce very similar limiting velocities, the variation in sensitivities results in some vehicles being limited more by one factor while some vehicles are limited more by the other, with an overall average speed somewhat lower than either of the limiting velocities. The smaller the value chosen for β, the more this average speed approaches the lower of the two limiting velocities.

The World Bank[80] used Brazilian data to estimate β for six vehicle classes, deriving values of 0.24 to 0.31. After comparing the effects of values of 0.01, 0.1 and 0.3 on the behavior of the FFS equation, TRDF recommended a value of 0.1 for all vehicle classes.[81]

In Equation 5.43, σ^2 is described by the World Bank as the variance of the logarithm of section-specific errors of observed speed. The World Bank's estimates[82] for σ^2 are between 0.007 and 0.036; and TRDF[83] suggests using 0.01. The effect of these values for σ^2 is a small upward adjustment in FFS (of about 0.5 percent using $\sigma^2 = 0.01$, and about 1.8 percent using $\sigma^2 = 0.036$). For simplicity, the effect of σ^2 has been omitted from the HERS equation.

Setting $\beta = 0.1$ and $\sigma^2 = 0$, Equation 5.43 becomes:

$$FFS = ((1/\mathrm{VCURVE})^{10} + (1/\mathrm{VROUGH})^{10} + (1/\mathrm{VSPLIM})^{10})^{-0.1} \qquad \textit{Eq. 5.44}$$

where VCURVE is given by Equation 5.39, VROUGH by Equations 5.41 and 5.42, and VSPLIM is derived from the section's speed limit as described above.

Equation 5.44 produces estimates of free-flow speed that are always below the lowest of the limiting velocities in the equation, but are exceedingly close to that velocity whenever that velocity is appreciably smaller than the other limiting velocities.

5.4.2 The Effects of Grades on Free-Flow Speed

Using an SAIC algorithm[84], HERS next calculates free-flow speed in the uphill direction (FFSUP) for trucks[85]. (For "personal vehicles" - automobiles and pickup trucks

80. Watanatada *et al.*, *op. cit.*, Table 4.3(a), p. 85.
81. Elkins, *et al.*, *op. cit.*, p. 156.
82. Watanatada *et al.*, Table 4.3(c), p. 86. The reference uses σ_e^2 to represent our σ^2.
83. Elkins, *et al.*, *op. cit.*, p. 156.
84. Science Applications International Corporation, *et al.*, *Speed Determination Models for the Highway Performance Monitoring System*, pp 78-79.

- HERS assumes that grades have no effect on free-flow speed.) First, crawl speed for the section is estimated as follows:

$$CRAWLS = 1/(j + k \times GRADE) \qquad \textbf{Eq. 5.45}$$

where:

CRAWLS	=	Crawl speed in miles per hour;
j, k	=	constants which depend upon vehicle characteristics; and
GRADE	=	the average grade of the section (expressed as a fraction).

The values used for constants *j* and *k* are shown in Table 5-14[86].

Table 5-14. Values of Crawl Speed Constants by Truck Type

Vehicle Type	*j*	*k*
6-Tire Truck	0.0090	0.0815
3-4 Axle Truck	0.0090	0.2755
4-Axle Combination	0.0090	0.2755
5-Axle Combination	0.0090	0.2755

HERS then calculates the delay due to grades:

$$DGRADE = \begin{cases} a(1 \angle \exp(b/a)) + b & \text{if } CRAWLS < FFS \\ 0 & \text{otherwise} \end{cases} \qquad \textbf{Eq. 5.46}$$

where:

$$b = SLEN(1/CRAWLS \angle 1/FFS) \qquad \textbf{Eq. 5.47}$$

$$\imath = \angle 0.05(1/CRAWLS \angle 1/FFS)^{0.6} \qquad \textbf{Eq. 5.48}$$

DGRADE	=	delay in hours; and
SLEN	=	length of the section

The delay due to grades is then combined with free-flow speed to yield free-flow speed uphill, FFSUP:

$$FFSUP = 1/(1/FFS + DGRADE/(SLEN)) \qquad \textbf{Eq. 5.49}$$

85. Since the HPMS database does not contain any information on the direction of grades, one-way facilities are treated in the same way as two-way facilities; i.e., as if traffic may be moving either uphill or downhill.
86. Science Applications International Corporation, *et al.*, *Speed Determination Models for the Highway Performance Monitoring System*, Table 3-3, and Herbert Weinblatt, "The Effects of Grades on Truck Speed," memorandum, Cambridge Systematics, Inc., Feb. 25, 1998.

5.4.3 Delay Due to Congestion and Traffic Control Devices

The CSI/SAIC algorithms address four types of highway conditions based upon number of lanes and the presence of traffic control devices. HERS identifies two additional conditions, defining a total of six highway classifications for use within the speed model. Table 5-15 lists the salient characteristics of each of the six classifications, and indicates which of the equations are used for each classification. Note that the number of lanes is not a factor when either signals or stop signs are present on the section.

Table 5-15. HERS Highway Classifications and the Delay Algorithms

Total Lanes in Both Directions	Stop Signs	Traffic Signals	HERS Classification	Algorithms Used
N/A	Yes	No	Sections with Stop Signs	Urban Arterials with Unsignalized Intersections
N/A	No	Yes	Sections with Traffic Signals	Urban Arterials with Signalized Intersections
N/A	Yes	Yes	Sections with Stop Signs and Traffic Signals	Both: Urban Arterials with Unsignalized Intersections and Urban Arterials with Signalized Intersections
2	No	No	Free-Flow Sections, One Lane per Direction	Two-Lane Rural Sections
3	No	No	Free-Flow Sections, Three-Lane Two-way	Two-lane Rural Sections and modified Freeways and Multilane Rural Highways
4 or more	No	No	Free-Flow Sections, Two or More Lanes per Direction	Freeways and Multilane Rural Highways

Each of the implemented algorithms consists of two or more equations. Selection of the appropriate equation hinges upon the ratio of the section's Annual Average Daily Traffic (AADT) to the section's two-way peak hour capacity[87]. This AADT/Capacity ratio is referred to as the *ACR*. Each of the routines below yields delay in hours per 1000 vehicle miles. HERS converts this to average effective speed using the equation:

$$AES = 1/(1/FFS + D/1000) \qquad \textbf{\textit{Eq. 5.50}}$$

where:

AES = Average Effective Speed;
FFS = Free Flow Speed (or FFS Uphill), as calculated above; and
D = average delay in hours per 1000 vehicle miles, with delay due to incidents, other congestion, and/or traffic control devices.

87. Other than in the calculation of the AADT/Capacity ratio (used in the speed calculations and the elasticity calculations), capacity generally means one-way capacity (except for two-lane rural roads) as reported in the HPMS data records.

The procedures used for estimating delay on multi-lane free-flow sections and on sections with traffic signals develop separate estimates of delay due to incidents, due to other congestion, and due to traffic signals (where present). For other types of sections, the procedures used do not estimate incident delay. For these sections, estimates of delay due to crashes are inferred from HERS' estimates of the delay cost of crashes (see section 5.3.4.1), and these estimates are used (without further adjustment) as estimates of delay due to incidents.

5.4.3.1 Sections with Stop Signs

For roads with stop signs, HERS selects an equation based upon both the AADT/Capacity ratio and the number of stop signs per mile. The equations are presented in Table 5-16.

Table 5-16. Delay Equations for Sections with Stop Signs

AADT/C Range	Stop Signs/ mile	
<6		$D_{ss} = N_{sspm} \times (1.9 + 0.067 \times FFS + 0.103 \times ACR + 0.0145 \times ACR^2)$
>6 and <15	<10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS \angle 0.029 \times (ACR \angle 6)^2) + 0.354 \times (ACR \angle 6)^2$
	>10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS) + 0.064 \times (ACR \angle 6)^2$
>15	<10	$D_{ss} = N_{sspm} \times (0.691 + 0.067 \times FFS) + 0.354 \times (ACR \angle 6)^2$
	>10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS) + 0.354 \times (ACR \angle 6)^2 \angle 23.49$

where:

D_{ss}	=	Delay due to stop signs and non-incident congestion in hours per 1000 vehicle miles;
N_{sspm}	=	Number of stop signs per mile (average);
FFS	=	Free flow speed (or free flow speed uphill); and
ACR	=	the AADT/Capacity ratio for the section.

Total delay on these roads is estimated as the sum of the above delay plus delay due to crashes (per 1,000 vehicle-miles). The latter value is generated by HERS' safety analysis (see 5.3.4.1).

5.4.3.2 Sections with Traffic Signals

For sections with traffic signals, HERS uses modified versions of the CSI/SAIC equations[88] in a multi-step process to estimate traffic volume and delay in the peak period (separately by direction) and in the offpeak period. The variables below are used in the equations contained in Table 5-17 through Table 5-20 (for sections with traffic signals) and also Table 5-22 through Table 5-25 (for free-flow sections).

88. Cambridge Systematics, Inc., Harry Cohen, and Science Applications International Corp., *Sketch Methods for Estimating Incident-Related Impacts*, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 1998, Section 2.3; and Cambridge Systematics, Inc., *2000 Revisions to HERS*, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., August 2002.

ACR	=	ratio of AADT to two-way capacity during the off-peak period
BPM	=	bottlenecks per mile (set to 0.083 for multi-lane free-flow sections and 0.5 for sections with traffic signals)
CPCAP	=	capacity during peak periods in the counter-peak direction (one way)
CPLANES	=	through lanes in peak period, counter-peak direction
DFAC	=	directional factor
FFS	=	free-flow speed (mph)
NSIG	=	number of signalized intersections per mile (average)
OP2WCAP	=	two-way capacity during off-peak period
PKCAP	=	capacity during peak period in peak direction (one way)
PLANES	=	through lanes in peak period, peak direction

Index K, K = 1, 2, or 3

1	=	peak period, peak direction
2	=	peak period, counter-peak direction
3	=	off-peak period

DINC(K)	=	incident-related delay (hours per million vehicle-miles) in period/direction K (K = 1, 2, 3)
NITR(K)	=	travel rate (hours per vehicle-mile) without incidents in period/direction K (K = 1, 2, 3)
SHFAC	=	shoulder factor (based on left and right shoulder widths, see Table 5-26)
TRAVF(K)	=	fraction of annual travel in period/direction K (K = 1, 2, 3)
VCRPP(K)	=	peak-period volume/capacity ratio – average hourly volume in the indicated direction during a three-hour peak period divided by capacity (K = 1 for peak direction, 2 for counter-peak direction)
ZVDSIG	=	zero-volume delay due to traffic signals (hours per vehicle-mile

The steps of this process are:

1. Divide total traffic volume into peak period volume (in the peak and counterpeak directions, separately) and offpeak volume. Table 5-17 displays the equations for fraction of travel for signalized arterials.
2. Estimate the peak-hour Volume/Capacity ratios for the peak and counter-peak directions. The equations for volume-to-capacity for signalized arterials are defined in Table 5-18.
3. Estimate the “zero-volume delay” (relative to free-flow speed) that is due to traffic signals. This is the expected delay that a single vehicle would encounter if it were the only vehicle on the road. The equation for estimating the zero-volume delay is:

$$ZVDSIG = 0.0687 \times (1 - e^{-NSIG/24.4}) \quad \textbf{\textit{Eq. 5.51}}$$

Table 5-17. Fraction of Travel for Signalized Arterials

Peak/Off-Peak	Condition	Fraction of Travel
Off-Peak	ACR ≤ 7	TRAVF(3) = 0.7106
	ACR > 7 and ACR ≤ 9	TRAVF(3) = 0.7106 - 0.00160 (ACR-7) + 0.00240 $(ACR-7)^{1.48} e^{-0.0431(ACR-7)}$
	ACR > 9 and ACR ≤ 12	TRAVF(3) = 0.7074 - 0.00227 (ACR-9) + 0.00240 $(ACR-7)^{1.48} e^{-0.0431(ACR-7)}$
	ACR > 12	TRAVF(3) = 0.7006 + 0.00373 (ACR-12) + 0.00240 $(ACR-7)^{1.48} e^{-0.0431(ACR-7)}$
Peak	Peak Direction	TRAVF(1) = DFAC * (1 – TRAVF(3))
	Counter-peak Direction	TRAVF(2) = (1 – DFAC) * (1 – TRAVF(3))

Table 5-18. Volume-to-Capacity Ratios for Peak Periods for Signalized Arterials

Direction	Volume-to-Capacity Ratio
Peak Direction	$VCRPP(1) = 0.243 \times ACR \times TRAVF(1) \times OP2WCAP/PKCAP$
Counter-peak Direction	$VCRPP(2) = 0.243 \times ACR \times TRAVF(2) \times OP2WCAP/CPCAP$

4. Estimate the average "travel rate" (i.e., the inverse of speed, in hours per vehicle-mile) in the absence of incidents. The model develops separate estimates for the peak period (by direction) and for the offpeak period. These values include the effects of zero-volume delay. The equations for travel rate for signalized arterials are defined in Table 5-19.

Table 5-19. Travel Rate Without Incidents for Signalized Arterials

Peak/Off-Peak	Condition	Travel Rate (hours per vehicle-mile)
Off-Peak Period	ACR ≤ 7	NITR(3) = (1/FFS+ZVDSIG) (1 + 0.0213 $ACR^{1.05}$)
	ACR > 7 and ACR ≤ 11	NITR(3) = (1/FFS+ZVDSIG)(1 + 0.0213 $ACR^{1.05}$) + 4.56E-08 BPM $(ACR-7)^{8.25} e^{-0.561 (ACR-7)}$
	ACR > 11	NITR(3) = (1/FFS+ZVDSIG) (1.05 + 0.0247 ACR – 0.000504 ACR^2 + 2.68E-06 ACR^3) + 4.56E-08 x BPM x $(ACR-7)^{8.25} e^{-0.561 (ACR-7)}$
Peak Period	VCRPP(K) ≤ 0.5767	NITR(K) = (1/FFS+ZVDSIG) (1 + 0.455 $VCRPP(K)^{1.02}$)
	VCRPP(K) > 0.5767	NITR(K) = (1/FFS + ZVDSIG)(0.889 + 0.680 x VCRPP(K) + 0.0423 $VCRPP(K)^2$ – 0.182 $VCRPP(K)^3$) + 0.228 BPM $(VCRPP(K) - 0.5767)^{2.66} e^{3.61 (VCRPP(K)-0.5767}$

5. Estimate additional delay due to incidents (per vehicle-mile) for the peak period (by direction) and for the offpeak period. Table 5-20 displays the equations for incident delay for signalized arterials.

Table 5-20. Incident Delay for Signalized Arterials

Peak/Off-Peak	Condition	Incident Delay (hours per vehicle-mile)
Off-Peak Period	ACR ≤ 11	DINC(3) = 7.52E-06 (ACR) $^{1.11}$ e $^{0.132\ ACR}$
	ACR > 11	DINC(3) = 7.74E-09 (ACR) $^{5.20}$ e $^{-0.135\ ACR}$
Peak Period	VCRPP(K) ≤ 0.5767	DINC(K) = 0.000111 (VCRPP(K)) $^{-0.828}$ e $^{2.83\ VCRPP(K)}$
	VCRPP(K) > 0.5767	DINC(K)= 1.34E-06 (VCRPP(K)) $^{-2.05}$ e $^{7.74\ VCRPP(K)}$

6. The results of Steps 4 and 5 are combined to produce estimates of average speed overall and separately for the peak and offpeak periods. The general formula for this step is:

$$AES = 1/(NITR + D_{inc}) \qquad \textbf{Eq. 5.52}$$

where:

AES	=	Average Effective Speed;
$NITR$	=	Non-Incident Travel Rate (hours per vehicle-mile); and
D_{inc}	=	Delay due to incidents (hours per vehicle-mile).

This procedure produces estimates of overall average speed, average speed in the peak and offpeak periods, and three components of delay (relative to free-flow speed): zero-volume delay, incident delay, and other congestion delay.

5.4.3.3 Sections With Stop Signs and Traffic Signals.

To calculate the average effective speed for sections with both types of traffic control devices, HERS calculates two speeds over the section: one, as if all the devices were stop signs, and two, as if all the devices were signals. HERS then averages these speeds together, weighted by the ratio of traffic signals to stop signs.

5.4.3.4 Free-Flow Sections, One Lane per Direction

The equation selection for two-lane roads depends only upon the AADT/Capacity ratio. The equations are presented in Table 5-21.

Table 5-21. Delay Equations for 2-lane, 2-way Roads

AADT/C Range	
< 10	$D_{cong1} = 0.432 \times ACR$
> 10	$D_{cong1} = 9.953 \angle 1.66 \times ACR + 0.109 \times ACR^2$

where:

D_{cong1}	=	average delay due to non-incident congestion in hours per 1000 vehicle miles; and

ACR = the AADT/Capacity ratio for the section.

Total delay on these roads is estimated as the sum of the above delay plus delay due to crashes (per 1,000 vehicle-miles). The latter value is generated by HERS' safety analysis (see 5.3.4.1).

5.4.3.5 Free-Flow Sections, Three-Lane Two-Way

For three-lane, two-way roads without traffic control devices, HERS assumes that the volume is split evenly between the two directions, and that capacity is split 7:5 in favor of the two-lane direction. This is implemented by multiplying the section's AADT/Capacity ratio by 0.857 to derive the AADT/Capacity ratio in the two-lane direction, and by 1.2 to derive the AADT/Capacity ratio in the one-lane direction. These modified AADT/Capacity ratios are then used in the respective delay calculations. HERS calculates the delay in the single-lane direction using the equations for two-lane rural roads, and in the two-lane direction using the multilane equations. HERS then figures total delay as the average of the two.

5.4.3.6 Free-Flow Sections, Two or More Lanes per Direction

For sections with at least two lanes in each direction and no traffic signals or stop signs, HERS uses modified versions of the CSI/SAIC equations[89] in a multi-step process to estimate traffic volume and delay in the peak period (separately by direction) and in the offpeak period. The procedure produces estimates of overall average speed, average speed in the peak and offpeak periods, and two components of delay: incident delay and other congestion delay.

The steps of this process are:

1. Divide total traffic volume into peak period volume (in the peak and counterpeak directions, separately) and offpeak volume. The equations for fraction of travel for free-flow sections with two or more lanes per direction are defined in Table 5-22.

Table 5-22. Fraction of Travel for Free-Flow Sections

Peak/Off-Peak	Condition	Fraction of Travel
Off-Peak Period	ACR ≤ 7	$TRAVF(3) = 0.6970$
	ACR > 7 and ACR ≤ 9	$TRAVF(3) = 0.6970 \angle 0.00085(ACR \angle 7) + 0.00212(ACR \angle 7)^{1.39} \times e^{\angle 0.00798(ACR \angle 7)}$
	ACR > 9 and ACR ≤ 12	$TRAVF(3) = 0.6953 \angle 0.00187(ACR \angle 9) + 0.00212(ACR \angle 7)^{1.39} \times e^{\angle 0.00798(ACR \angle 7)}$
	ACR > 12	$TRAVF(3) = 0.6897 \angle 0.00408(ACR \angle 12) + 0.00212(ACR \angle 7)^{1.39} \times e^{\angle 0.00798(ACR \angle 7)}$
Peak Period	Peak Direction	$TRAVF(1) = DFAC \times (1 \angle TRAVF(3))$
	Counter-peak Direction	$TRAVF(2) = (1 \angle DFAC) \times (1 \angle TRAVF(3))$

89. Cambridge Systematics, Inc., Harry Cohen, and Science Applications International Corp., *Sketch Methods for Estimating Incident-Related Impacts*, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 1998, Section 2.3; and Cambridge Systematics, Inc., *2000 Revisions to HERS*, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., August 2002.

2. Estimate the peak-hour Volume/Capacity ratios for the peak and counter-peak directions. The equations for volume-to-capacity for free-flow sections with two or more lanes per direction are defined in Table 5-23.

Table 5-23. Volume-to-Capacity Ratios for Peak Periods for Free-Flow Sections

Direction	Volume-to-Capacity Ratio
Peak Direction	$VCRPP(1) = 0.243 \times ACR \times TRAVF(1) \times OP2WCAP / PKCAP$
Counter-peak Direction	$VCRPP(2) = 0.243 \times ACR \times TRAVF(2) \times OP2WCAP / CPCAP$

3. Estimate the average "travel rate" (i.e., the inverse of speed, in hours per vehicle-mile) in the absence of incidents. The model develops separate estimates for the peak period (by direction) and for the offpeak period. These values include the effects of zero-volume delay. The equations for travel rate for free-flow sections with two or more lanes per direction are defined in Table 5-24

Table 5-24. Travel Rate Without Incidents for Free-Flow Sections

Peak/Off-Peak	Condition	Travel Rate (hours per vehicle-mile)
Off-Peak Period	ACR ≤ 7	$NITR(3) = (1/FFS) \times (1 + 9.19 \times 10^{-11} \times ACR^{7.71})$
	ACR > 7 and ACR ≤ 11	$NITR(3) = (1/FFS) \times (1 + 9.19 \times 10^{-11} \times ACR^{7.71}) + 0.00000133 \times BPM \times (ACR - 7)^{6.97} \times e^{-0.356 \times (ACR - 7)}$
	ACR > 11	$NITR(3) = (1/FFS) \times (1.0367294 - 0.0169 \times ACR + 0.00177 \times ACR^2 - 0.0000407 \times ACR^3) + 0.00000133 \times BPM \times (ACR - 7)^{6.97} \times e^{-0.356 \times (ACR - 7)}$
Peak Period	VCRPP(K) ≤ 0.5995	$NITR(K) = (1/FFS) \times (1 + 0.388 \times VCRPP(K)^{7.27})$
	VCRPP(K) > 0.5995	$NITR(K) = (1/FFS) \times (1.4060195 - 1.84 \times VCRPP(K) + 2.54 \times VCRPP(K)^2 - 0.985 \times VCRPP(K)^3) + 0.00000133 \times BPM \times (VCRPP(K) - 0.5995)^{2.54} \times e^{1.94 \times (VCRPP(K) - 5.995)}$

4. Estimate additional delay due to incidents (per vehicle-mile) for the peak period (by direction) and for the offpeak period. The equations for incident delay[90] for free-flow sections with two or more lanes per direction are defined in Table 5-25. Table 5-26 presents the shoulder factors used in these equations.

90. These equations produce values of DINC in hours per vehicle-mile for consistency with the corresponding equations for sections with traffic signals (in Section I.3). The equations in the HERS code for multi-lane free-flow sections (but not those for sections with traffic signals) actually produce values in hours per million vehicle-miles that are subsequently converted to hours per thousand vehicle-miles and hours per vehicle-mile as needed.

Table 5-25. Incident Delay for Free-Flow Sections

Peak/Off-Peak	Number of Lanes per Direction	Condition	Incident Delay (hours per vehicle-mile)
Off-Peak Period	2	ACR ≤ 11	$DINC(3) = 4.05 \times ACR^{\angle 0.251} \times e^{(0.603 \times ACR)} \times SHFAC$
		ACR > 11	$DINC(3) = 3.55826 \times 10^{\angle 11} \times ACR^{17.1} \times e^{\angle 0.865 \times ACR} \times SHFAC$
	3	ACR ≤ 11	$DINC(3) = 0.789 \times ACR^{\angle 0.834} \times e^{0.854 \times ACR} \times SHFAC$
		ACR > 11	$DINC(3) = 3.41342 \times 10^{\angle 11} \times ACR^{16.9} \times e^{\angle 0.847 \times ACR} \times SHFAC$
	4 or more	ACR ≤ 11	$DINC(3) = 0.153 \times ACR^{\angle 0.881} \times e^{1.01 \times ACR} \times SHFAC$
		ACR > 11	$DINC(3) = 3.2672 \times 10^{\angle 11} \times ACR^{16.8} \times e^{\angle 0.82 \times ACR} \times SHFAC$
Peak Period	2	VCRPP(K) ≤ 0.5995	$DINC(K) = 4.6 \times VCRPP(K)^{\angle 0.247} \times e^{9.2 \times VCRPP(K)} \times SHFAC$
		VCRPP(K) > 0.5995	$DINC(K) = 29173.1 \times VCRPP(K)^{5.16} \times e^{\angle 0.789 \times VCRPP(K)} \times SHFAC$
	3	VCRPP(K) ≤ 0.5995	$DINC(K) = 0.011 \times VCRPP(K)^{\angle 2.3} \times e^{16.9 \times VCRPP(K)} \times SHFAC$
		VCRPP(K) > 0.5995	$DINC(K) = 560567 \times VCRPP(K)^{7.99} \times e^{\angle 3.92 \times VCRPP(K)} \times SHFAC$
	4 or more	VCRPP(K) ≤ 0.5995	$DINC(K) = 0.00035 \times VCRPP(K)^{3.19} \times e^{21.8 \times VCRPP(K)} \times SHFAC$
		VCRPP(K) > 0.5995	$DINC(K) = 5841010 \times VCRPP(K)^{10.1} \times e^{\angle 6.12 \times VCRPP(K)} \times SHFAC$

Table 5-26. Shoulder Factors (SHFAC)

Number of Lanes per Direction	Number of Six Foot (or wider) Shoulders in Each Direction		
	0	1	2
2	5.22	3.04	1.00
3	4.77	2.83	1.00
4 or more	4.45	2.68	1.00

5. The results of Steps 4 and 5 are combined to produce estimates of average speed overall and separately for the peak and offpeak periods using Equation 5.52.

5.4.4 Distance Traveled Between Traffic Control Devices

HERS uses the distance travelled between stops when traversing a section as an input to the operating cost model. HERS assumes that drivers stop at all stop signs, and at traffic signals when they are red. For sections with stop signs, this distance is simply the length of the section divided by the number of traffic control devices. For sections with traffic signals, HERS allows for signals which might be green and not require a stop.

5.5 Travel Time Costs

HERS incorporates U.S. Department of Transportation values of time per person for personal travel and for business travel.[91] Table 5-27, “Value of One Hour of Travel Time (1995 Dollars),” presents a summary of the major components of the revised HERS estimates of the 1995 value of travel time, by vehicle type. The values used for each of the components are documented below.

Table 5-27. Value of One Hour of Travel Time (1995 Dollars)

	Small Auto	Med. Auto	4-Tire Truck	6-Tire Truck	3-4 Axle Truck	4-Axle Comb.	5-Axle Comb.
Business Travel							
Value per Person	$ 18.80	$ 18.80	$ 18.80	$ 16.50	$ 16.50	$ 16.50	$ 16.50
Avg. Occupancy	1.43	1.43	1.43	1.05	1.0	1.12	1.12
Vehicle	$ 1.09	$ 1.45	$ 1.90	$ 2.65	$ 7.16	$ 6.41	$ 6.16
Inventory	-	-	-	-	-	$ 0.60	$ 0.60
Personal Travel							
Value per Person	$ 8.50	$ 8.50	$ 8.50	-	-	-	-
Avg. Occupancy	1.67	1.67	1.67	-	-	-	-
Percent Personal	89%	89%	75%	-	-	-	-
Avg Value per Vehicle	**$ 15.71**	**$ 15.75**	**$ 17.84**	**$ 19.98**	**$ 23.66**	**$ 25.49**	**$ 25.24**

For the purpose of indexing the value of time from 1995 dollars to dollars of a subsequent year, HERS allows separate indexing of the value of time per person, the vehicle cost, and inventory-cost components. The indexes currently used for the three components are, respectively: The U.S. Bureau of Labor Statistics (BLS) Employment Cost Index for total compensation of all civilian workers; U.S. Department of Commerce Bureau of Economic Analysis (BEA) data on average expenditures per car; and the implicit gross domestic product (GDP) price deflator, also obtained from BEA. The index values used to convert these components to 1997 dollars (for the 1999 *C&P Report*) are, respectively: 1.059, 1.110, and 1.038.

5.5.1 Vehicle Occupants

HERS obtains the value of time to vehicle occupants from the U.S. Department of Transportation (USDOT) Departmental Guidance.[92] The values used are the values (in 1995 dollars) for travel via surface modes. For on-the-clock travel for all occu-

91. U. S. Department of Transportation, “The Value of Saving Travel Time: Departmental Guidance for Conducting Economic Evaluations,” April 1997, Table 4.
92. *Ibid*.

pants of four-tire vehicles, HERS uses the recommended value for "business travel" ($18.80 per person-hour), while the value used for all occupants of larger vehicles is the slightly lower recommended value for truck drivers ($16.50 per person-hour). For personal travel, HERS uses the recommended value for personal local travel ($8.50 per person hour).[93]

5.5.2 Average Vehicle Occupancy

HERS derives values for average vehicle occupancy (AVO) of four-tire vehicles from 1995 National Personal Travel Survey (NPTS)[94] estimates of VMT and person-miles of travel by trip type. The NPTS data indicates that AVO for "work-related business" (exclusive of commuting) is 1.43, while AVO for all other purposes is 1.67.

For combination trucks, AVO was set to 1.12 on the basis of Hertz' analysis of the frequency of the use of two-driver teams in crash-involved trucks.[95] Six-tire vehicles, which include pick-up-and-delivery vehicles that sometimes carry a helper, were assumed to have an average occupancy of 1.05, while heavier single-unit trucks were assumed to have only one occupant.

5.5.3 Personal-Use Percentage of VMT

Approximately 4.7 percent of automobiles are estimated to be in commercial fleets of four or more vehicles, excluding fleet vehicles that are individually leased or used for daily rental;[96] and 6.7 percent of the VMT of the remaining automobiles is for work-related business.[97] These figures indicate that just under 89 percent of automobile VMT represents personal travel (including commuting), while the remainder represents business travel.

For four-tire trucks, the percentage of VMT that was not for personal use was 31 percent in 1992;[98] however, this percentage has undoubtedly dropped in the last several years as small truck-based vehicles have become increasingly popular as personal vehicles. Accordingly, HERS assumes that personal use accounts for 75 percent of the VMT of four-tire trucks and business use accounts for 25 percent of this VMT.

93. The Departmental Guidance recommends using a higher value ($11.90 per person-hour) for personal intercity travel, implying that, at least in rural areas, an average value for personal travel that is slightly higher than $8.50 might be appropriate. (HERS does not accept separate values of personal travel time and vehicle occupancy for business and personal travel. The input values of personal travel time and vehicle occupancy used by HERS 3.2 for four-tire vehicles are set so that, when combined with weighted averages of the average vehicle occupancy values in Table 5-27, they will produce the overall average values of time shown at the bottom of the table.)
94. Oak Ridge National Laboratories, *1995 National Personal Travel Survey*, Table NPTS-1, October 1997 (www-cta.ornl.gov/npts/1995/doc/table1.pdf).
95. Robin P. Hertz, "Sleeper Berth Use as a Risk Factor for Tractor Trailer Driver Fatality," *31st Annual Proceedings, American Association for Automotive Medicine*, September 1987, pp. 215-227.
96. American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1995*, Detroit, 1995, pp. 39 and 43.
97. Oak Ridge National Laboratories, *op. cit*.
98. U. S. Bureau of the Census, *1992 Truck Inventory and Use Survey*, May 1995.

5.5.4 Vehicle Costs

Vehicles depreciate as a result of their use and as a result of aging that is independent of vehicle use. The former type of depreciation is estimated by HERS' vehicle operating-cost procedure, while the latter type is a time-related cost incurred by all vehicle owners and included as a component of travel-time cost of commercial vehicle operators. For HERS 3.2, time-related depreciation was estimated by:

1. Estimating total annual depreciation by vehicle type, and converting these estimates to costs per hour of vehicle operation;
2. Using a modified version of HERS to obtain estimates of usage-related depreciation (by vehicle type) per vehicle-mile; and
3. Converting the latter estimates to costs per hour of vehicle operation, and subtracting from the Step 1 results.[99]

The estimation process is described below.

For autos in commercial motor pools and four-tire trucks, total depreciation per hour was computed as the average vehicle cost per year (assuming a five-year life, with a 15 percent salvage value at the end, with initial cost from the American Automobile Manufacturers Association[100]) divided by 2,000 hours per year of sign-out time (essentially the day shift or other shift when maximal vehicle use occurs). For heavier trucks, total depreciation per hour was computed as the average vehicle cost per year[101] divided by the number of hours in service per year. Six-tire trucks and four-axle combination trucks were assumed to be in service 2,000 hours per year; and five-axle combinations were assumed to be in service 2,200 hours per year. Because three- and four-axle single-unit trucks include many dump trucks that have down time between jobs, especially during cold periods of the winter, they were assumed to be used only 1,600 hours per year.

The resulting estimates of total depreciation per hour of operation are shown in the first column of Table 5-28. The relatively high value shown for three- and four-axle single-unit trucks is the result of the low number of hours per year that they are used and relatively small differences between the initial costs of these vehicles and those of tractor-trailer combinations.

The second column of Table 5-28 shows estimates of average annual mileage for the seven vehicle types distinguished by HERS. Annual mileage for automobiles is from *Highway Statistics*;[102] and annual mileage for the five categories of trucks is from the *1992 Truck Inventory and Use Survey*.[103]

99. In earlier versions of HERS, Steps 2 and 3 were not performed. Thus, usage-related depreciation was included in HERS estimates of travel-time costs as well as HERS estimates of operating costs. The new procedure is designed to eliminate this double counting.

100. American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996*, Detroit, 1996, p. 60.

101. Estimates of average vehicle cost per year are those used in the *1997 Federal Highway Cost Allocation Study* (U.S. Department of Transportation, July 1997). Sources used in developing these estimates were: Jack Faucett Associates, "The Effect of Size and Weight Limits on Truck Costs," prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1990; Maclean Hunter Market Reports, *The Truck Blue Book*, January 1995, Chicago (sales prices for tractors and chassis); U.S. Bureau of the Census, *Current Industrial Reports, Truck Trailers*, summaries for various years (price adjustments for trailers); and a survey of truck dealers (prices for single-unit trucks).

102. Federal Highway Administration, *Highway Statistics 1997*, November 1999, Table VM-1.

Table 5-28. Estimation of Vehicle Costs (1995 Dollars)

Vehicle Type	Total Depreciation ($/hr.)	Miles per Year[a]	Mileage-Related Depreciation ($/mile)	Mileage-Related Depreciation ($/hr.)	Time-Related Depreciation ($/hr.)
Small Autos	$ 1.72	11,575	$0.109	$ 0.63	$ 1.09
Medium/Large Autos	2.02	11,575	0.098	0.57	1.45
Four-Tire Trucks	2.18	12,371	0.045	0.28	1.90
Six-Tire Trucks	3.08	10,952	0.079	0.43	2.65
3+ Axle Trucks	8.80	15,025	0.175	1.64	7.16
3-4 Axle Combinations	7.42	35,274	0.057	1.01	6.41
5+ Axle Combinations	7.98	66,710	0.060	1.82	6.16

a. For automobiles, from Federal Highway Administration, *Highway Statistics 1997*, November 1999, Table VM-1; for trucks, from U. S. Bureau of the Census, *1992 Truck Inventory and Use Survey,* May 1995, Table 2a.

The third column of Table 5-28 shows the estimates of mileage-related depreciation, in cents per mile. The estimates of annual hours of operation presented above and those of annual miles per year shown in the second column of the table were then used to convert the estimates of mileage-related depreciation to dollars per hour (as shown in the fourth column); and this result was subtracted from total depreciation to produce the estimates of time-related depreciation that are shown in the last column of Table 5-28, and also in Row 3 of Table 5-27.

The estimates of time-related depreciation and mileage-related depreciation shown in the fourth and fifth columns of Table 5-28 are internally consistent in that, for each vehicle type, the two values add up to the estimate of total depreciation (in the first column). These two sets of estimates are thus appropriate for use by HERS (or by any similar system making joint use of both sets of estimates). However, some of the individual values in the last three columns do raise questions. In particular, the values for mileage-related depreciation for trucks appear to be low relative to the corresponding values for automobiles.[104] A brief investigation into the causes of this result suggests that it probably is due to differences between the procedures used for automobiles and those used for trucks in the original estimation of mileage-related depreciation.[105]

103. *Op. cit.*, Table 2a.

104. A comparison of Columns 4 and 1 indicates that mileage-related depreciation accounts for 28 percent of total depreciation of medium/large automobiles and 37 percent of depreciation for small automobiles. The corresponding figures for the three types of single-unit trucks are only about half as large (13 to 19 percent). Even for five-axle combinations, which have average annual mileages that are five times those of automobiles, mileage-related depreciation represents only 23 percent of total depreciation. Observing that styling obsolescence is a significant contributor to time-related depreciation for automobiles but not for trucks, this suggests that, for vehicles with comparable annual mileages, mileage-related depreciation probably should be smaller for automobiles than for trucks.

105. J. P. Zaniewski, *et. al.*, *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*, Texas Research and Development Foundation, prepared for FHWA, June 1982, pp. 60-67.

5.5.5 Inventory Costs

To compute the inventory costs for five-axle combination trucks, an hourly discount rate was computed and multiplied by the value of a composite average shipment. The discount rate selected was 9.8 percent, equal to the average prime bank lending rate in 1995 plus one percent. Dividing this rate by the number of hours in a year produces an hourly discount rate is 0.0033 percent. The average payload of a five-axle combination is about 35,000 pounds. In 1993, the average value of commodities shipped by truck was $1.35 per pound (on a ton-mile weighted basis).17 Inflating to 1995 dollars using the GDP deflator and multiplying by the average payload produces an average payload value of roughly $50,000. The resulting time value of the average payload is approximately $0.60 per hour (ignoring any costs for spoilage and depreciation over time).

Payload for four-axle combination trucks is lower than for five-axle combination trucks, but the value of the cargo probably is higher. Consequently, the value per shipment was assumed to be the same for both types of trucks.

5.5.6 Estimating Travel Time Costs

For each vehicle type, these values are used by HERS to develop estimates of travel time costs on each section from the equation:

$$TTCST_{vt} = \frac{1000}{AES_{vt}} \times TTVAL_{vt} \qquad \textbf{Eq. 5.53}$$

where:

$TTCST_{vt}$	=	average travel-time cost (in 1995 dollars per thousand vehicle-miles) for vehicles of type *vt*;
AES_{vt}	=	average effective speed of vehicles of type *vt* on the highway section being analyzed; and
$TTVAL_{vt}$	=	average value of time (in 1995 dollars) for occupants and cargo of vehicles of type *vt* (as shown on the bottom line of Table 5-27).

For each section, the average travel-time cost (per thousand vehicle-miles) is obtained by taking a weighted average of the corresponding costs for each vehicle type. In HERS the weights are obtained by using section-specific HPMS data on the percentages of four-tire vehicles, single-unit trucks, and combination trucks, and then allocating these percentages to the seven vehicle types using distributions (by functional system) obtained from the HPMS Vehicle Classification Study[106] (see section 2.11 “The Fleet Composition Model” on page 2-15).

5.6 The Travel Forecast Model

The 1999 version of HERS introduced travel demand elasticity to the travel forecast model. See Appendix B, “Induced Traffic and Induced Demand” for a discussion of

106. U. S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System Analytical Process *Technical Manual*, Version 2.1, December 1987, Table IV-20.

the concepts guiding these modifications to HERS. See Appendix C, "Demand Elasticities for Highway Travel" for a discussion of appropriate elasticity values for use in HERS. Appendix D, "Basic Theory of Highway Project Evaluation" presents the principles that apply generally to evaluating highway improvements.

This section first addresses the tasks performed by HERS during initialization:

- estimating the baseline price;
- setting the baseline V/C; and
- determining the adjusted initial volume.

It then discusses the specific steps utilized by the model in:

- forecasting baseline travel;
- adjusting the baseline forecast for long run elasticity; and
- applying the short run elasticity to yield a traffic volume forecast.

5.6.1 Initialization: Assuming the Baseline Price

The section input data includes AADT for the data year and also for a future data year, typically 20 years beyond the data year. HERS generally assumes that the future volume forecast is based upon a continuation of the initial level of service, as defined by volume-to-capacity (V/C) ratio and PSR. The exception is congested sections, in which case HERS assumes the forecast includes an improvement to increase capacity. HERS calculates the initial user price as the sum of the operating, travel time, and safety costs at the beginning of the analysis period and saves the initial V/C ratio as the baseline V/C level. The baseline price is set equal to the initial price. However, if the section's initial V/C ratio is equal to or greater than one, then HERS sets the baseline V/C level to one, and calculates the baseline price at a volume consistent with a V/C of one and a minimum PSR of two.

HERS next calculates an initial adjusted volume for the section at the beginning of the analysis period. The adjusted volume is used as the "departure point" for the calculation of future baseline traffic volumes. During initialization, HERS calculates adjusted volume:

$$VADJ = (AADT/(INPRI^{SRE})) \times BASPRI^{SRE} \qquad \textbf{Eq. 5.54}$$

where:

VADJ	=	adjusted volume at beginning of analysis period;
AADT	=	reported volume -- AADT at beginning of analysis period;
INPRI	=	initial price to user at beginning of analysis period;
BASPRI	=	baseline price; and
SRE	=	short run elasticity.

Note that, for sections with initial V/C less than one, the adjusted volume will equal the reported volume because the initial price is equal to the baseline price. For sections with initial V/C greater than one, the re-calculated baseline price is likely to be lower than the initial price (the lower level of congestion should lower travel time costs). As a result, the adjusted volume should be higher than the initial volume, and reflects backing out the effects of short run elasticity.

5.6.2 Applying Elasticity to Travel Volume Forecasts

To calculate future traffic volume, HERS performs the following steps:

- project future baseline traffic volume by applying the section-specific growth factor to the adjusted present volume;
- determine the future adjusted volume by applying long run elasticity to the baseline projection;
- apply short run elasticity to the adjusted volume to produce an initial, estimated volume;
- using the initial estimate as a departure point, perform a simultaneous solution to determine the equilibrium point between the demand and delay functions to arrive at a final traffic volume.

The model applies elasticity separately to each funding period. When the traffic prediction model calculates the volume after a time span of more than one funding period, it calculates the volume for each funding period successively. The calculation period for volume prediction is from the midpoint of one funding period to the midpoint of the following funding period, a schedule which coincides with the implementation of improvements (at the middle of the funding period) and the benefit-cost analysis period.

The baseline projection begins with the adjusted volume from the “current” funding period (that is, the last period for which volume data is known). The adjusted volume represents the volume on the section before the application of within period short run elasticity. As shown in Equation 5.55, any of the baseline forecast options discussed in section 3.3.3.7 “Traffic Growth Rates” on page 3-24 may be used in the calculation of baseline traffic volume at time t_1 from previous long run adjusted volume (at time t_0):

$$VBASE_{t_1} = \begin{cases} VADJ_{t_0} + (AAGRSL \times LFP) \\ VADJ_{t_0} \times AADTGR^{LFP} \\ 2 \times (VADJ_{t_0} + (AAGRSL \times LFP)) \angle VADJ_{t_0} \times AADTGR^{LFP} \end{cases} \qquad \textbf{\textit{Eq. 5.55}}$$

where:

$VBASE_{t1}$	=	baseline traffic volume at the midpoint of funding period t_1;
$VADJ_{t0}$	=	adjusted traffic volume at the midpoint of the previous funding period t_0;
$AAGRSL$	=	linear growth rate (see section 5.6.2);
$AADTGR$	=	constant growth rate (see section 5.6.2); and
LFP	=	the length of a funding period.

HERS next applies the long run share of elasticity to get adjusted volume at time t_1:

$$VADJ_{t_1} = VBASE_{t_1} \times (1 + LRS \times (FINPRI_{t_0} \angle BASPRI)/(BASPRI)) \qquad \textbf{Eq. 5.56}$$

where:

$VADJ_{t1}$	=	the adjusted volume at time t_1;
$VBASE_{t1}$	=	the baseline volume at time t_1 (from Equation 5.55);
LRS	=	the long run share;
$FINPRI_{t0}$	=	the final user price at time t_0, based upon the AADT at time t_0; and
$BASPRI$	=	the baseline price.

Short run elasticity is applied to the adjusted volume to estimate an initial volume:

$$VINIT_{t_1} = ALPHA \times FINPRI_{t_0}^{SRE} \qquad \textbf{Eq. 5.57}$$

where:

$VINIT_{t1}$	=	the initial volume at time t_1;
$ALPHA$	=	$VADJ_{t_1}/BASPRI^{SRE}$; and
SRE	=	short run elasticity.

5.6.3 The Simultaneous Solution

To locate a point on the demand curve, knowing the price is sufficient to determine volume. If the price were constant with respect to volume, there would be a simple functional relationship with a single argument. However, as both demand and price vary with volume, HERS must find a simultaneous resolution of the supply and demand functions. The equilibrium is the intersection of the supply and demand.

For most of the components of price to the highway user, price does not vary with volume (that is, the rate of flow). Pavement condition is related to cumulative usage (not immediate volume), and the effects of volume-to-capacity (V/C) on accident costs is not well understood, so these are treated as unit costs invariant with flow volume. The exception is congestion, which is clearly related to V/C, although the relationship is not precisely known.

Starting with a price (p_0) that includes all components other than delay, and a demand curve, the volume (v_0) is determined from the price, as shown in Figure 5-2. To this price, adding the additional cost for delay, measured off the curve marked "price of delay," generates the upper curve "price with delay." At the price with delay corresponding to the initial volume, p_d, demand would be reduced to some point to the left of the vertical axis (this axis is not at zero volume); delay, however, would be largely eliminated, so the price would no longer apply at this volume. The correct solution is the circled point "equilibrium," which balances the increase in price with the reduction in congestion.

Ideally, this equilibrium point could be found by solving for the intersection of the two functions. While the demand curve is either a straight line or a constant elasticity curve, either of which is a simple single-valued function with two parameters, the

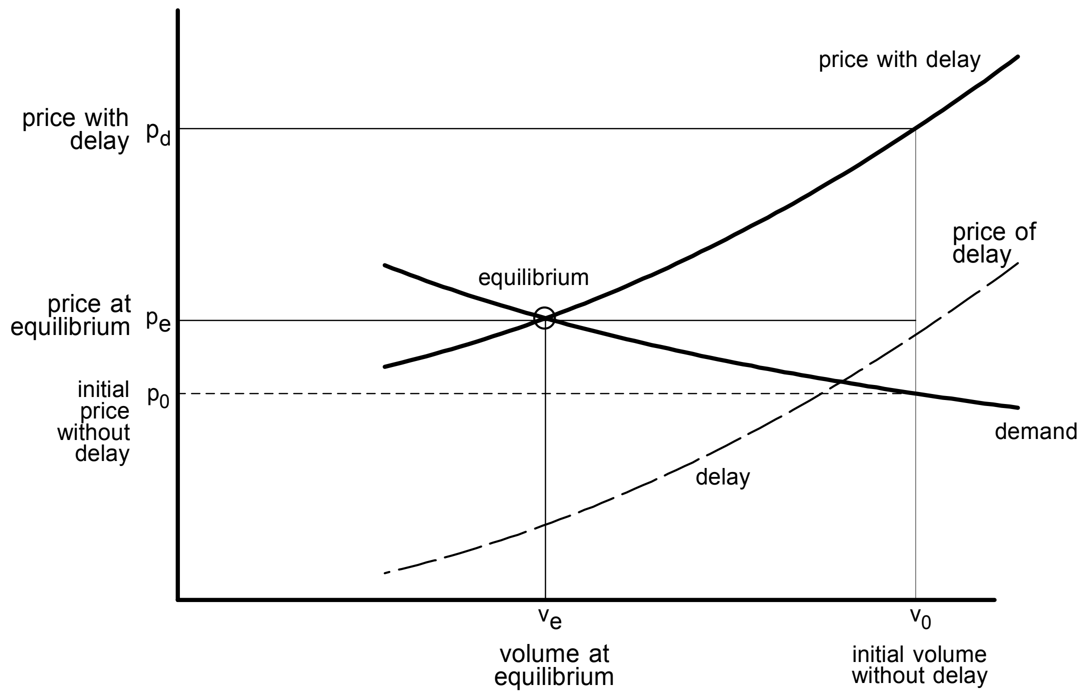

Figure 5-2. Adjustment of Calculated Delay for Congestion Reduction

delay curve is more complex. The delay curve differs with each of the six road types, and for three of these has different equations for different volume levels. Because of the variety and complexity of these equations, closed-form solutions to the supply-demand intersection are not feasible. Numerical solutions could be obtained to any precision desired, but convergence under all possible conditions would be difficult to ensure, and computational effort might be excessive.

HERS instead uses the alternative approach of a numerical approximation, whose properties are:

1. Rapid convergence because of the smooth shapes of the demand and delay functions; and
2. A fixed number of iterations (two) which necessarily limits computational effort.

This strategy is acceptable because a high degree of numerical precision is not required; the only purpose is to adjust the volume of traffic to a reasonable level given congestion and other generalized price factors.

The approximation strategy uses the slopes of the two curves to estimate the intersection as the apex of a triangle (as if the curves were straight lines), and uses the resulting volume adjustment to re-estimate the slopes as the average of two slopes. In Figure 5-3, the first iteration is shown in heavy solid lines, and the second iteration in heavy dashed lines. The first iteration uses the tangents at the initial volume, *VINIT,* shown as $sdlay_i$ and $sdem_i$ (for delay and demand, respectively), to yield the volume *RVOL* and the price $Price_{RVOL}$. Averaging the demand slope at *RVOL* with that for *VINIT* ($sdem_i$) gives the arc slope of the demand curve (shown as $sdem_r$) between

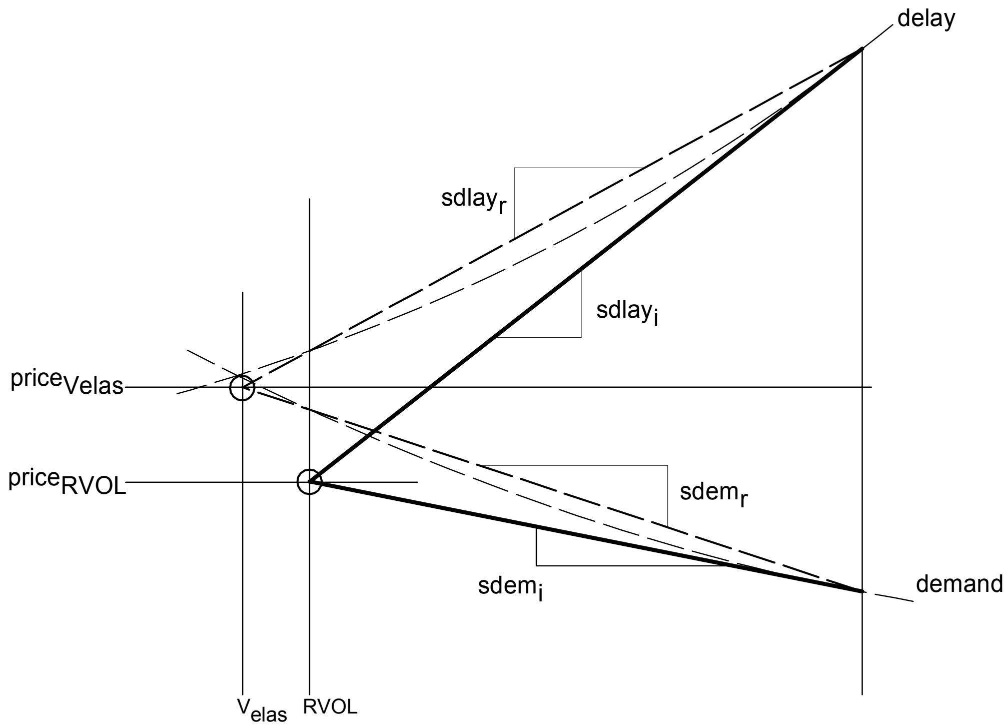

Figure 5-3. Details of Successive Approximation

those two points, which is a much closer approximation of the slope between the equilibrium and the initial volumes than is the tangent at *VINIT*. Doing the same for the delay function gives the revised delay slope $sdlay_r$, and applying the two revised slopes to *VINIT* produces the second-iteration result of volume V_{elas} and price $Price_{Velas}$. This is still not the true equilibrium point, but it is close enough.

The lower the AADT/Capacity ratio, the more accurate this procedure becomes. The situation displayed in Figure 5-3 is an extreme scenario, in that *VINIT* represents an AADT/Capacity ratio of 19.5, which means the facility is operating at capacity for 15-19 hours per day. For AADT/C under 12, the second iteration is almost indistinguishable from the first, and for AADT/C under 8 the first iteration is indistinguishable from the equilibrium.

5.6.4 Computational Algorithms

HERS performs a sequence of steps preparatory to the simultaneous solution of the demand and supply functions. HERS first calls upon the pavement model to determine the condition of the pavement at time t_1 based upon the initial volume estimate. Using this provisional PSR and the initial volume, HERS:

- determines free flow speed and free flow speed uphill for each vehicle type;
- using the free flow speeds, determines the travel time cost without delay;
- calculates the operating costs at the baseline level of service (that is, with the volume to the same level relative to capacity as per the baseline price);

- calculates the safety costs at the initial volume at time t_1; and
- sums the travel time, operating, and safety costs to yield "price without delay" (*PWOD*).

HERS first calculates the slope of the initial demand curve:

$$SDEM_i = \frac{PWOD^{(1 \angle SRE)}}{ALPHA \times SRE} \qquad \textbf{Eq. 5.58}$$

where:

$SDEM_i$	=	initial slope of demand curve; and
PWOD	=	price without delay.

HERS then calculates an initial estimate of the amount of delay at the volume *VINIT* at time t_1, ($EDLAY_i$) and calculates the slope of the delay function ($SDLAY_i$) at that volume. The specific algorithms are based upon the SAIC/CS equations used in the speed model, and like them are dependent upon the road type, the AADT/Capacity ratio, and the number of traffic signals and stop signs per mile, if any. The equations for specific road types are in Table 5-29 and Table 5-30 in section 5.6.5, "Delay Equations by Road Type." The examples below (in Equations 5.59 and 5.60) are for two-lane, two-way roads without traffic control devices where the AADT/Capacity ratio (figured using the initial volume as AADT) is less than 10. The initial estimate of delay is determined:

$$EDLAY_i = 0.432 \times \frac{VINIT}{Capacity} \times VOT/1000 \qquad \textbf{Eq. 5.59}$$

where:

$EDLAY_i$	=	estimate of delay at the initial volume;
VINIT	=	initial volume estimate (from Equation 5.57); and
VOT	=	value of an hour of travel time.

The slope of the delay equation at the initial volume is:

$$SDLAY_i = 0.432 \times VOT/(Capacity \times 1000) \qquad \textbf{Eq. 5.60}$$

where:

$SDLAY_i$	=	slope of the delay curve at the initial volume.

The first approximation for a revised volume is the height of a triangle (laying on its side) whose base is the initial estimate of delay and whose sides slope at $SDEM_i$ and $SDLAY_i$ (as shown in Figure 5-3):

$$RVOL = VINIT + \frac{EDLAY_i}{SDEM_i \angle SDLAY_i} \qquad \textbf{Eq. 5.61}$$

where:

RVOL	=	revised volume estimate
$EDLAY_i$	=	initial estimate of delay (from road type specific equation)

$SDLAY_i$	=	initial slope of delay function (from road type specific equation)

The model substitutes this revised volume for the initial volume in Equation 5.59 to yield a revised estimate of delay ($EDLAY_r$). (Note that the revised volume is also substituted for the initial volume in determining the AADT/Capacity ratio used to select the specific form of the equation.) HERS next calculates the price associated with the initial volume:

$$Price_{VINIT} = (VINIT/ALPHA)^{(1/(SRE))} \qquad \textbf{Eq. 5.62}$$

and the price associated with the revised volume:

$$Price_{RVOL} = (RVOL/ALPHA)^{(1/(SRE))} \qquad \textbf{Eq. 5.63}$$

The next step is the calculation of revised slopes for the demand and delay functions. The demand slope is taken as the difference between the initial and revised prices over the difference between their associated volumes:

$$SDEM_r = \frac{(Price_{RVOL} \angle Price_{VINIT})}{(RVOL \angle VINIT)} \qquad \textbf{Eq. 5.64}$$

where:

$SDEM_r$	=	revised demand slope

The delay slope is taken as the difference between the revised and initial delay estimates divided by the difference in the associated volumes:

$$SDLAY_r = \frac{(EDLAY_r \angle EDLAY_i)}{(RVOL \angle VINIT)} \qquad \textbf{Eq. 5.65}$$

where:

$SDLAY_r$	=	revised delay slope

HERS calculates the price of delay at the intersection of the revised slopes:

$$Price_{Delay} = EDLAY_i \times \frac{SDEM_r}{(SDEM_r \angle SDLAY_r)} \qquad \textbf{Eq. 5.66}$$

and uses it to estimate the final, elasticized volume, V_{elas}:

$$V_{elas} = ALPHA \times (PWOD + Price_{Delay})^{SRE} \qquad \textbf{Eq. 5.67}$$

The process used to determine delay for sections with signals and multi-lane freeflow sections (for which see paragraphs 5.4.3.2 and 5.4.3.6) is not conducive to the development of equations (such as those in Tables 5-29 and 5-30 below) useful in the procedure described above. For such sections, the elasticity procedure makes successive calls to the congestion/delay routines (described in section 5.4.3) with slightly different input volumes in order to estimate the slope of the delay curve.

5.6.5 Delay Equations by Road Type

These tables contain the delay equations used during the simultaneous solution for two-lane, two-way roads without traffic control devices, and for the two-lane direction of three-lane, two-way roads without traffic control devices. (The calculations for the single lane direction of the three-lane road employ the equations used for the two-lane, two-way road.) Within each road type, equations are selected based upon the AADT/Capacity ratio and the number of stop signs per mile. The equations are based upon the SAIC[107] and CSI[108] equations implemented in the speed model. The equations yielding *EDLAY* (the estimated delay) would replace Equation 5.59 in the computations detailed above. The equations yielding *SDLAY* (the slope of the delay function) would replace Equation 5.60 as used above.

The “wheres” below apply to the delay equations in Tables 5-29 through 5-30:

EDLAY	=	estimate of delay (equation substitutes for Equation 5.59)
SDLAY	=	delay slope (equation substitutes for Equation 5.60)
ACR	=	AADT/Capacity Ratio
VOT	=	value of an hour of travel time for the section
NSS	=	the average number of stop signs per mile
NTS	=	the average number of traffic signals per mile
FFS	=	free flow speed for the section
COMPF	=	the factor $1 \angle \exp(\angle NTS / 24.4)$

The two hybrid road types are treated in the same manner as in the speed model. On sections with both stop signs and traffic signals, the final elasticized volume is the average of the volumes on the two portions of the section, weighted by the relative numbers of stop signs and signals. On three-lane sections in two directions, volume is split equally between the two directions, and capacity is split 7:5 in favor of the two-lane direction. Elasticity is applied using the equations for rural multilane roads (in the two-lane direction) and two-lane roads (in the one-lane direction). The sum of the elasticized volumes is taken as the final elasticized volume for the section.

5.7 Agency Costs and Benefits

For agencies in charge of building and maintaining highways, HERS recognizes two potentially accruing benefits resulting from improving a highway section:

- a reduction in the cost of routine maintenance resulting from resurfacing or reconstruction of pavement; and

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107. Science Applications International Corporation and Cambridge Systematics, Inc., *Roadway Usage Patterns: Urban Case Studies*, prepared for Volpe National Transportations Systems Center and the Federal Highway Administration, June 1994, Appendix A; Science Applications International Corporation, *et al*., *Speed Determination Models for the Highway Performance Monitoring System*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, October 31, 1993.

108. Cambridge Systematics, Inc., *Revisions to the HERS Speed and Operating-Cost Procedures*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, January 25, 1996, Section 2.

Table 5-29. Delay Equations for the Two-Lane Direction of Three-Lane Roads

AADT/C Range	
<8	$EDLAY = (0.0797 \times ACR + 0.00385 \times ACR^2) \times VOT/1000$
	$SDLAY = (0.0797 + 0.00385 \times 2 \times ACR) \times VOT/(Capacity \times 1000)$
>8 and <12	$EDLAY = (12.1 \angle 2.95 \times ACR + 0.193 \times ACR^2) \times VOT/1000$
	$SDLAY = (\angle 2.95 + 0.193 \times 2 \times ACR) \times VOT/(Capacity \times 1000)$
>12	$EDLAY = (19.6 \angle 5.36 \times ACR + 0.342 \times ACR^2) \times VOT/1000$
	$SDLAY = (\angle 5.36 + 0.342 \times 2 \times ACR) \times VOT/(Capacity \times 1000)$

Table 5-30. Delay Equations for 2-lane, 2-way Roads

AADT/C Range	
< 10	$EDLAY = 0.432 \times ACR \times VOT/1000$
	$SDLAY = 0.432 \times VOT/1000$
> 10	$EDLAY = (9.953 \angle 1.66 \times ACR + 0.109 \times ACR^2) \times VOT/1000$
	$SDLAY = (\angle 1.66 + 0.218 \times ACR) \times VOT/(Capacity \times 1000)$

- a reduction in the cost of the next improvement resulting from the improved condition of the section when that improvement is implemented.

The second type of benefit is referred to as the “residual value” of the improvement. The estimation of residual value is discussed at some length in conjunction with the presentation of the HERS benefit-cost analysis procedure under section 7.7 “Residual Value” on page 7-5. The HERS procedure for estimating the other type of agency benefit, reductions in maintenance costs, is presented below. These benefits take their place in the numerator of the benefit-cost equation.

In HERS, all improvements are analyzed over a benefit-cost analysis (BCA) period that begins at the midpoint of one funding period and ends at the midpoint of some subsequent funding period. To simplify the analysis of maintenance expenditures, a “maintenance cost (MC) period” is defined as a period beginning at the midpoint of a funding period and ending at the midpoint of the next funding period. Estimates of pavement maintenance expenditures over each MC period are then derived from PSR estimates for the beginning and end of each period.

5.7.1 Maintenance Costs for Flexible Pavements

Estimates of maintenance costs per lane-mile for flexible pavements have been developed by Witczak and Rada[109] as a function of PSR and structural number (SN). Their results are presented in Table 5-31. The middle column of this table presents estimates of maintenance costs (in 1984 dollars) incurred per lane-mile during periods when PSR (PSI in the exhibit) drops from 4.5 to 4.0, from 4.0 to 3.5, etc. The last column shows estimates of cumulative maintenance costs per lane-mile for a section that starts with a PSR of 4.5 and has various indicated terminal PSRs ranging from 4.0 to 1.5. These estimates are independent of the time required for the deterioration to occur.

Table 5-31. Maintenance Costs for Flexible Pavements[a]
(1984 Dollars)

Final PSI	Maintenance Cost Between PSI Levels ($/lane mile)	Cumulative Cost ($/lane mile)
Low SN/traffic: (SN = 2.16)		
4.0	221.57	221.57
3.5	767.03	988.60
3.0	1,314.95	2,302.55
2.5	1,859.47	4,163.02
2.0	2,413.74	6,576.76
1.5	2,957.34	9,534.10
Medium SN/traffic: (SN = 3.60)		
4.0	339.10	339.10
3.5	1,174.05	1,513.15
3.0	2,012.72	3,525.87
2.5	2,845.76	6,371.63
2.0	3,604.98	10,066.61
1.5	4,526.45	14,593.06
High SN/traffic: (SN = 5.04)		
4.0	456.63	456.63
3.5	1,581.05	2,037.38
3.0	2,710.50	4,748.18
2.5	3,832.04	8,580.22
2.0	4,976.21	13,556.43
1.5	6,095.55	19,651.98

109. Matthew W. Witczak and Gonzalo R. Rada, *Microcomputer Solution of the Project Level PMS Life Cycle Cost Model*, University of Maryland, Department of Civil Engineering, prepared for Maryland Department of Transportation, State Highway Administration, Baltimore, Md., December 1984, Chapter 4.

a. Source: Matthew W. Witczak and Gonzalo R. Rada, *Microcomputer Solution of the Project Level PMS Life Cycle Cost Model*, University of Maryland, Department of Civil Engineering, prepared for Maryland Department of Transportation, State Highway Administration, Baltimore, MD., December 1984, p. 132

Regressing the values for cumulative maintenance costs shown in Table 5-31 against the values for PSR (or PSI) and SN yields the following equation:

$$COST = 4427.24 \angle 1989.7 \times PSR + 223.57 \times PSR^2 + 7996.11 \times SN \angle 3594.56 \times SN \times PSR + 403.99 \times SN \times PSR^2 \qquad \textbf{\textit{Eq. 5.68}}$$

where:

PSR	=	terminal PSR;
SN	=	structural number; and
COST	=	where cost is cumulative maintenance cost per lane-mile, in 1984 dollars, for the time over which the pavement is deteriorating from an initial PSR of 4.5 to the terminal PSR.

The R^2 for the above equation exceeds 0.9999.

Equation 5.68 can be modified to produce cost estimates in 1988 dollars by multiplying all coefficients by 1.2118, the ratio of the 1988 and 1984 values of FHWA's Cost Index for Highway Maintenance and Operation.[110]

To estimate maintenance costs per lane-mile on any section during a period beginning at time *i* and ending at time *f*, Equation 5.68 is evaluated using the section's PSR at times *i* and *f*, and the difference between the two results is obtained. The general form of the HERS equation to provide this result, MCOST, in 1988 dollars, is:

$$MCOST = \angle (2411 + 4355 \times SN) \times (PSR_f \angle PSR_i) + (270.9 + 489.6 \times SN) \times (PSR_f^2 \angle PSR_i^2) \qquad \textbf{\textit{Eq. 5.69}}$$

This equation (Equation 5.69) would produce negative values of *MCOST* whenever $PSR_i > PSR_f \geq 4.5$. To avoid this undesirable effect, 4.5 is substituted for any PSR values above 4.5. The resulting costs can be adjusted to dollars of another year. To index the 1988 dollars to 1997 dollars for use in the 1999 *Conditions and Performance Report*, a factor of 1.231 was used for rural sections and 1.242 for urban sections.[111]

110. U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics: 1988*, U.S. Government Printing Office, Washington, D.C., 1989, Table PT-5.

111. Indexing since 1988: Office of Program Administration, *Price Trends for Federal-Aid Highway Construction*, U.S. Department of Transportation, Federal Highway Administration, Washingon, D.C., quarterly.

5.7.2 Maintenance Costs for Rigid Pavements

In the absence of readily available information about maintenance costs for rigid pavements, HERS assumes these costs are identical to those for flexible pavements with a structural number (SN) of 5.625. This is the SN of flexible pavements with a thickness of 5.5 inches, the thickest flexible pavement considered by HERS.

5.8 External Costs

The HERS model includes estimates of the costs of damages from vehicular emissions of air pollutants in its calculation of benefits and disbenefits resulting from the implementation of an improvement. HERS employs a set of tables that specify the average cost of air pollutant emissions generated per vehicle-mile by the three different HERS vehicle classes operating at various speeds on each of the nine HERS roadway functional classes. HERS uses the projected mix of vehicle classes and the average speed of travel on each sample section to determine the average cost of emissions per vehicle-mile, and multiplies this value by its forecast of total vehicle-miles to calculate the total cost of air pollutant emissions generated by travel on the section.

The effect of a proposed improvement to a sample section on air pollution costs is measured by the difference between total pollution costs generated by the forecast volumes of travel on the section under baseline and improved conditions. Because the cost of air pollutant emissions per vehicle-mile varies both by travel speed and among vehicle classes, this effect can be negative (a benefit) or positive (a disbenefit) depending on how a proposed improvement affects forecast travel volumes, the mix of vehicle types, and travel speeds on a sample section.

HERS' estimates of the average cost of air pollutant emissions per vehicle-mile for each of its three vehicle classes differ among the nine HERS roadway functional classes for several reasons:

- each of HERS' three vehicle classes includes several specific types of vehicles, which have different emission rates per vehicle-mile, and the exact mix of these individual vehicle types making up each vehicle class differs slightly among HERS' nine roadway functional classes;
- emission rates per vehicle-mile for the same type of vehicle traveling at the same average speed differ among collector, arterial, and freeway sections because the specific patterns of driving that produce a given average speed tend to differ among these roadway types;
- the density of development typically found along roadway sections located in urban areas is much higher than for rural functional classes, resulting in increased population exposure to air pollutant emissions and higher costs per mile of travel by all classes of vehicles on urban sections.

The average cost of air pollutant emissions per vehicle-mile for each HERS vehicle class and roadway functional class also declines gradually over future years. The decline in air pollution costs reflects projected reductions in the rates at which all types of vehicles emit various air pollutants, as well as projected changes in the composition of the U.S. vehicle fleet and the resulting mix of vehicle classes operating on each roadway functional class.

Air pollution costs during future years for each HERS vehicle class and roadway functional class are estimated by applying an annual rate of decline to the appropriate values for the year 2000. The average annual rate of decline in air pollution costs for each vehicle and roadway functional class was calculated by fitting an exponential function (which represents a constant annual percentage rate of decline) using detailed estimates of air pollution costs prepared for the years 2000 and 2020.

Table 5-32 below provides an example of HERS' estimates of air pollution damage costs. It shows average air pollution costs per vehicle-mile of travel at selected speeds, for each of HERS' three vehicle classes operating on Urban Arterial sections during the year 2000. Table 5-32 reveals the typical patterns of variation in air pollution costs: at each speed, costs are higher for single-unit trucks than for four-tire vehicles (automobiles and light-duty trucks), and highest for combination trucks, while costs for each vehicle class decline significantly from very low speeds through moderate speeds (30-40 mph), after which they increase gradually. Appendix G of this report includes similar tables for each of the nine roadway functional classes employed by HERS, including a complete discussion of the derivation of these costs.

Table 5-32. Air Pollution Costs by Vehicle Class and Average Travel Speed: Urban Arterial Sections

Average Speed (mph)	Emission Damage Cost per Vehicle-Mile of Travel ($2000)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	0.0358419	0.0560533	0.1275028
6	0.0316863	0.0514504	0.1211734
7	0.0287181	0.0481626	0.1166524
8	0.0264919	0.0456968	0.1132616
9	0.0247604	0.0437789	0.1106243
10	0.0233752	0.0422446	0.1085145
…			
30	0.0153292	0.0296437	0.0786490
31	0.0152326	0.0295601	0.0784381
32	0.0151421	0.0294816	0.0782404
33	0.0150570	0.0294080	0.0780546
34	0.0149769	0.0293386	0.0778798
35	0.0149014	0.0292732	0.0777150
36	0.0148982	0.0292916	0.0786260
37	0.0148952	0.0293089	0.0794878
38	0.0148923	0.0293254	0.0803043
39	0.0148896	0.0293410	0.0810789
40	0.0148870	0.0293558	0.0818147
41	0.0148946	0.0294674	0.0818474
42	0.0149019	0.0295736	0.0818786
43	0.0149088	0.0296749	0.0819083
44	0.0149155	0.0297716	0.0819367
45	0.0149218	0.0298640	0.0819638
46	0.0149325	0.0300613	0.0831937
47	0.0149427	0.0302503	0.0843713
48	0.0149524	0.0304313	0.0854998
49	0.0149618	0.0306050	0.0865823
50	0.0149708	0.0307717	0.0876214
…			
60	0.0151521	0.0341296	0.1095182
61	0.0151613	0.0347254	0.1136012
62	0.0151702	0.0353021	0.1175524
63	0.0151789	0.0358604	0.1213782
64	0.0151872	0.0364013	0.1250845
65	0.0151953	0.0369255	0.1286767
66	0.0152034	0.0374580	0.1323721
67	0.0152116	0.0379988	0.1361736
68	0.0152198	0.0385481	0.1400843
69	0.0152280	0.0391061	0.1441073
70	0.0152362	0.0396728	0.1482459
r*	6.06%	7.79%	11.30%

Chapter 6:

Capital Cost of Improvements

HERS requires estimates of highway improvement costs to be included in the analysis of investment options. In the case of the pavement, widening and alignment improvements currently considered by HERS, these costs are all initial costs; i.e., they are incurred at the time the improvement is implemented. When analyzing the economic attractiveness of a potential improvement, the improvement cost is used as the denominator in the benefit-cost equation.

This chapter contains six parts. The first discusses how HERS divides the section into the portion receiving improved alignment (if any) and the portion receiving the identified improvement.

The second part presents the HERS procedure for estimating the initial cost of each of the HERS-type improvements.

The third part explicates the HERS procedure for estimating the initial cost of improvements which include a modified alignment.

The fourth section presents the process for combining the costs with and without alignment modification to determine the total cost of improving a section.

The fifth part of this chapter discusses the allocation of improvement costs between preservation and expansion.

The final portion of this chapter presents the state cost factors which (optionally) adjust the cost of improvements by state.

6.1 The Length of an Improvement

On sections receiving an alignment improvement, HERS only improves alignment over that portion of the section with deficient alignment. HERS improves the rest of the section with the specified improvement. Thus HERS identifies three lengths for sections undergoing improvement:

- *SLEN* – the length of the section (HPMS item 30);
- *LNEW* – the length of the portion of the section being re-aligned; and
- *IMPLEN* – the length of the section which will receive the specified improvement.

HERS identifies the length of the section to be re-aligned (*LNEW*) as:

$$LNEW = LAFTV \times OPT_V + LAFTH \times OPT_H \qquad \textbf{Eq. 6.1}$$

where:

$LAFTV$	=	length of corrected grades after re-alignment;
$LAFTH$	=	length of corrected curves after re-alignment;
OPT_V	=	1 if grades are being corrected by re-alignment, 0 otherwise; and
OPT_H	=	1 if curves are being corrected by re-alignment, 0 otherwise.

The PreProcessor determines the two values *LAFTV* and *LAFTH* when processing the section's geometrics. HERS limits *LNEW* to be less than or equal to *SLEN*. The length of the section to be improved without re-alignment (*IMPLEN*) is:

$$IMPLEN = SLEN \angle LNEW \qquad \textbf{\textit{Eq. 6.2}}$$

6.2 Pavement and Widening Improvements

HERS distinguishes nine elemental improvement costs, two of which are for improved alignment. Table 6-1, "Elemental Capital Improvement Costs," presents the scaled estimates of HERS improvement costs per lane-mile. These costs are national averages expressed in 2002 dollars but can be scaled to any other-year dollars by the user. The HERS costs include both improvement and right-of-way (ROW) costs, but do not include costs such as unusual cut and fill operations, excessive number of structures, or non-construction costs.

When adding lanes or re-aligning pavement, HERS distinguishes between costs incurred at "normal" and "high" cost. The cost level is determined by the interaction between each section's widening feasibility code (*WDFEAS*, HPMS item 62) and the section's functional class' widening feasibility override code. (For a more detailed discussion, see section 4.3, "The Widening Feasibility Model," page 4-26.) While under certain circumstances HERS will add both normal and high cost lanes in a single improvement, if any high cost lanes are added to a section HERS will perform any re-alignment on that section at high cost.

Three of the costs (for shoulders and the two add lanes costs) are incremental: that is, they are added to other improvements costs when costing the improvement.

6.2.1 Resurfacing Pavement

HERS computes the cost of resurfacing a section as:

$$RS_{Cost} = IMPLEN \times XLANES \times D_{HwyGrp} \qquad \textbf{\textit{Eq. 6.3}}$$

where:

RS_{Cost}	=	the cost of the resurfacing improvement;
$IMPLEN$	=	the length of the improvement;
$XLANES$	=	the number of existing lanes; and
D_{HwyGrp}	=	the lane-mile cost to resurface, from column D of Table 6-1, with the row determined by the section's Highway Group.

Table 6-1. Elemental Capital Improvement Costs
(Thousands of 2002 Dollars per Lane-Mile)

	A	B	C	D	E	F	G	H	I
	Reconstruct and Widen Lanes	Reconstruct Pavement	Resurface and Widen Lanes	Resurface Pavement	Improve Shoulders	Add Lane at Normal Cost	Add Lane at High Cost	Re-Align Pavement at Normal Cost	Re-Align Pavement at High Cost
Rural Interstate									
Flat terrain	1182	772	669	274	51	1899	2633	2106	10948
Rolling terrain	1325	792	770	292	84	2059	3331	2665	11444
Mountainous terrain	1564	916	927	322	129	2638	8315	3120	12458
Rural Other Principal Arterials									
Flat terrain	923	618	558	220	34	1521	2178	1742	8882
Rolling terrain	1042	635	634	245	57	1629	2629	2103	9396
Mountainous terrain	1197	720	739	267	89	1981	7368	12000	12000
Rural Minor Arterials									
Flat terrain	844	543	520	195	32	1383	1941	1553	1553
Rolling terrain	1019	601	647	210	59	1585	2500	2000	2000
Mountainous terrain	1182	687	761	232	90	1951	7368	11500	11500
Rural Major Collectors									
Flat terrain	889	575	537	199	41	1436	1436	1553	8838
Rolling terrain	973	584	604	211	55	1468	1468	1910	10054
Mountainous terrain	1111	662	699	231	87	1730	6911	11000	11000
Urban Interstate, Other Freeways and Expressways									
Small Urban	1987	1376	1566	334	61	3116	11094	5235	13290
Small Urbanized	2136	1388	1620	395	81	3405	12121	5720	14939
Large Urbanized	3407	2272	2509	530	306	5699	60000	9574	60000
Urban Other Principal Arterials									
Small Urban	1732	1169	1433	280	62	2649	9430	4450	11131
Small Urbanized	1853	1183	1498	331	83	2870	10218	4822	12401
Large Urbanized	2647	1734	2192	416	267	4200	14953	6216	14288
Urban Minor Arterials and Collectors									
Small Urban	1276	883	1084	205	45	1956	6964	3287	8929
Small Urbanized	1337	893	1094	233	55	2061	7338	3463	10003
Large Urbanized	1800	1194	1496	286	150	2858	10173	4801	11179

6.2.2 Resurfacing Pavement with Shoulder Improvements

HERS computes the cost of resurfacing a section and improving shoulders as:

$$RSSH_{Cost} = IMPLEN \times XLANES \times D_{HwyGrp} + IMPLEN \times E_{HwyGrp} \times FT \quad \textbf{\textit{Eq. 6.4}}$$

where:

$RSSH_{Cost}$	=	the cost of the resurfacing with improved shoulders improvement;
$IMPLEN$	=	the length of the improvement;
$XLANES$	=	the number of existing lanes;
E_{HwyGrp}	=	the center-line mile cost to improve the shoulder on one side of the highway, from column E of Table 6-1, with the row determined by the section's Highway Group; and
FT	=	1 for one-way facility, 2 for two-way facility.

6.2.3 Resurfacing Pavement and Widening Lanes

As this improvement can be implemented with or without shoulder improvements, HERS uses either of these two algorithms to calculated the cost. When shoulders are not being improved:

$$RSWL_{Cost} = IMPLEN \times XLANES \times C_{HwyGrp} \quad \textbf{\textit{Eq. 6.5}}$$

where:

$RSWL_{Cost}$	=	the cost of resurfacing an widening lanes; and
C_{HwyGrp}	=	the lane-mile cost to resurface with wider lanes, from column C of Table 6-1, with the row determined by the section's Highway Group.

When shoulders are also being improved, HERS uses:

$$RSWL_{Cost} = IMPLEN \times XLANES \times C_{HwyGrp} + IMPLEN \times E_{HwyGrp} \times FT \quad \textbf{\textit{Eq. 6.6}}$$

where all terms are as defined above.

6.2.4 Resurfacing Pavement and Adding Normal Cost Lanes

HERS uses one of four possible algorithms when costing this improvement depending upon whether lane width and shoulders (or both) are being included in the improvement. The simplest algorithm is when neither lane width or shoulders are being improved:

$$RSNC_{Cost} = IMPLEN \times XLANES \times D_{HwyGrp} + IMPLEN \times NCLADD \times F_{HwyGrp} \quad \textbf{\textit{Eq. 6.7}}$$

where:

$RSNC_{Cost}$ = the cost of resurfacing and adding normal cost lanes;
$NCLADD$ = the number of normal cost lanes being added; and
F_{HwyGrp} = the lane-mile cost to add a lane at normal cost, from column F of Table 6-1, with the row determined by the section's Highway Group.

When the shoulders are to be improved, HERS uses:

$$\begin{aligned} RSNC_{Cost} = \; & IMPLEN \times XLANES \times D_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} + \\ & IMPLEN \times E_{HwyGrp} \times FT \end{aligned} \qquad \textbf{\textit{Eq. 6.8}}$$

When the existing lanes are to be widened (but shoulders not improved) HERS uses:

$$\begin{aligned} RSNC_{Cost} = \; & IMPLEN \times XLANES \times C_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} \end{aligned} \qquad \textbf{\textit{Eq. 6.9}}$$

thus substituting the base cost of resurfacing with wider lanes for simple resurfacing.

And when the section is to be resurfaced with wider lanes and shoulder improvements, and additional lanes added at normal cost, HERS uses:

$$\begin{aligned} RSNC_{Cost} = \; & IMPLEN \times XLANES \times C_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} + \\ & IMPLEN \times E_{HwyGrp} \times FT \end{aligned} \qquad \textbf{\textit{Eq. 6.10}}$$

using the base cost of resurfacing with wider lanes plus the cost of adding lanes plus the cost of shoulder improvements.

6.2.5 Resurfacing Pavement and Adding High Cost Lanes

The HERS algorithms for adding high cost lanes are the same as those for normal cost lanes with the addition of high cost lanes as an additional charge. This accomodates improvements which add lanes at both normal and high cost. If no normal cost lanes are added, then NCLADD is zero.

For simple resurfacing and adding lanes, some at high cost, HERS calculates:

$$\begin{aligned} RSHC_{Cost} = \; & IMPLEN \times XLANES \times D_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} + \\ & IMPLEN \times HCLADD \times G_{HwyGrp} \end{aligned} \qquad \textbf{\textit{Eq. 6.11}}$$

where:

$RSHC_{Cost}$ = the cost of resurfacing and adding high cost lanes; and
G_{HwyGrp} = the lane-mile cost to add a lane at high cost, from column G of Table 6-1, with the row determined by the section's Highway Group.

When shoulders are to be improved, HERS uses:

$$\begin{aligned} RSHC_{Cost} = {} & IMPLEN \times XLANES \times D_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} + \\ & IMPLEN \times HCLADD \times G_{HwyGrp} + \\ & IMPLEN \times E_{HwyGrp} \times FT \end{aligned} \qquad \textbf{Eq. 6.12}$$

When the existing lanes are to be widened without shoulder improvements, HERS calculates:

$$\begin{aligned} RSHC_{Cost} = {} & IMPLEN \times XLANES \times C_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} + \\ & IMPLEN \times HCLADD \times G_{HwyGrp} \end{aligned} \qquad \textbf{Eq. 6.13}$$

And when existing lanes are widened, shoulders are improved, and lanes added at high cost, HERS uses:

$$\begin{aligned} RSHC_{Cost} = {} & IMPLEN \times XLANES \times C_{HwyGrp} + \\ & IMPLEN \times NCLADD \times F_{HwyGrp} + \\ & IMPLEN \times HCLADD \times G_{HwyGrp} + \\ & IMPLEN \times E_{HwyGrp} \times FT \end{aligned} \qquad \textbf{Eq. 6.14}$$

6.2.6 Reconstrucing Pavement

HERS determines the cost of reconstructing existing pavements as:

$$RC_{Cost} = IMPLEN \times XLANES \times B_{HwyGrp} \qquad \textbf{Eq. 6.15}$$

where:

RC_{Cost}	=	the cost of reconstructing pavement; and
B_{HwyGrp}	=	the lane-mile cost to reconstruct pavement, from column B of Table 6-1, with the row determined by the section's Highway Group.

When HERS reconstructs pavements, it improves the shoulders to the design standard if necessary. HERS does not identify or cost "reconstruction with shoulder improvements" as a separate improvement type.

6.2.7 Reconstructing Pavement and Widening Lanes

HERS calculates the cost of reconstructing pavement and widening the existing lanes as:

$$RCWL_{Cost} = IMPLEN \times XLANES \times A_{HwyGrp} \qquad \textbf{Eq. 6.16}$$

where:

$RCWL_{Cost}$	=	the cost of reconstructing pavement and widening the existing lanes; and

A_{HwyGrp}	=	the lane-mile cost to reconstruct pavement with wider lanes, from column A of Table 6-1, with the row determined by the section's Highway Group.

6.2.8 Reconstructing Pavement and Adding Normal Cost Lanes

When reconstructing pavement and adding lanes at normal cost, HERS uses:

$$RCNC_{Cost} = IMPLEN \times XLANES \times B_{HwyGrp} + IMPLEN \times NCLADD \times F_{HwyGrp} \quad \textbf{Eq. 6.17}$$

where:

$RCNC_{Cost}$	=	the cost of reconstructing pavement and adding lanes at normal cost.

When the existing lanes are to be reconstructed and widened, and new lanes are to be added at normal cost, HERS calculates:

$$RCNC_{Cost} = IMPLEN \times XLANES \times A_{HwyGrp} + IMPLEN \times NCLADD \times F_{HwyGrp} \quad \textbf{Eq. 6.18}$$

6.2.9 Reconstructing Pavement and Adding High Cost Lanes

HERS costs pavement reconstruction and the addition of lanes at high (and possibly normal) cost as:

$$RCHC_{Cost} = IMPLEN \times XLANES \times B_{HwyGrp} + IMPLEN \times NCLADD \times F_{HwyGrp} + IMPLEN \times HCLADD \times G_{HwyGrp} \quad \textbf{Eq. 6.19}$$

where:

$RCHC_{Cost}$	=	the cost of reconstructing pavement and adding lanes at high cost.

When the existing lanes are to widened as well as being reconstructed, HERS uses:

$$RCHC_{Cost} = IMPLEN \times XLANES \times A_{HwyGrp} + IMPLEN \times NCLADD \times F_{HwyGrp} + IMPLEN \times HCLADD \times G_{HwyGrp} \quad \textbf{Eq. 6.20}$$

6.3 Calculating Alignment Costs

HERS performs re-alignment only on that portion of a section which is reported as deficient in alignment

As with improvements which add lanes, HERS performs alignment improvements at either normal or high cost dependent upon each section's widening feasibility code (WDFEAS) and the widening feasibility code override (WDFOVR) for the section's functional class. (See section 4.3, "The Widening Feasibility Model," page 4-26, for details on the widening feasibility mechanism.) Re-alignment is calculated at high cost when a section's WFEAS is one (meaning no widening is possible) or lanes are being added and some of those lanes are at high cost. Otherwise, re-alignment is calculated at normal cost.

To calculate alignment costs on a section, HERS uses:

$$ALIGN_{Cost} = LNEW \times ALLLANES \times HI_{HwyGrp} \qquad \textbf{Eq. 6.21}$$

where:

$ALIGN_{Cost}$	=	the cost of alignment improvement on the section;
$LNEW$	=	the length of the section undergoing alignment improvement;
$ALLLANES$	=	the total number of lanes on the section after improvement (that is, the sum of the existing lanes and any lanes being added); and
HI_{HwyGrp}	=	the lane-mile cost to re-align pavement, from columns H (normal cost) or I (high cost) of Table 6-1, with the row determined by the section's Highway Group.

6.4 Total Improvement Cost

For any section, HERS obtains the total initial improvement cost for combining pavement and widening improvements with alignment improvements by combining the cost of reconstructing part of the section on a modified alignment with the cost of the pavement and widening improvements made to the remainder of the section:

$$TOTIMP_{Cost} = (IMP_{Cost} + ALIGN_{Cost}) \times EXPFAC \qquad \textbf{Eq. 6.22}$$

where:

$TOTIMP_{Cost}$	=	the total expanded cost of the improvement;
IMP_{Cost}	=	the cost of improving the portion of the section which did not undergo re-alignment (as calculated using equations 6.3 through 6.20);
$ALIGN_{Cost}$	=	the cost of improving the portion of the section which was re-aligned (using equation 6.21); and
$EXPFAC$	=	the section's expansion factor.

6.5 Allocating Capacity and Preservation Costs

During the process of calculating the cost of an improvement HERS allocates the cost between the preservation of existing pavement and the expansion of capacity. HERS allocates the costs as follows (where the columns are those of Table 6-1):

1. Additional Lanes – The cost of new lanes is allocated to capacity expansion. These costs are calculated using columns F and G.

2. Widening Lanes – The difference between the base pavement improvement (resurfacing or reconstruction, column B or D) and the same pavement improvement with wider lanes (column A or C) is allocated to capacity expansion. The cost of the base pavement improvement is allocated to preservation.
3. Improving Shoulders – The cost of improving shoulders (column E) is allocated to preservation.
4. Pavement Improvement – The cost of improving pavement (column B or D) is allocated to preservation.
5. Alignment Modification – For the portion of a section receiving improved alignment (columns H and I), HERS prorates the allocation based upon the ratio of new and existing lanes to the total number of lanes.

6.6 State Cost Factors

HERS indexes improvement costs by state. The cost factors are derived from *Price Trends*[1] as a three-year rolling average, and are applied to all capital costs associated with the improvement. For the 2004 *C&P Report*, all the state cost factors were set to 1.0. Table 6-2 presents the index values used for the 2002 *C&P Report* (which used 2000 data).

1. Office of Infrastructure, *op. cit.*

Table 6-2. 2000 State Cost Factors[a]

State	Factor	State	Factor	State	Factor
AL	0.936	LA	1.016	OH	1.152
AK	1.831	ME	1.541	OK	1.054
AZ	0.855	MD	1.274	OR	1.329
AR	0.640	MA	1.805	PA	1.295
CA	1.262	MI	1.324	RI	0.840
CO	1.060	MN	1.222	SC	1.416
CT	1.009	MS	1.211	SD	0.857
DE	1.349	MO	0.846	TN	0.929
DC	1.018	MT	1.052	TX	0.687
FL	1.020	NE	0.927	UT	0.957
GA	1.091	NV	1.019	VT	1.232
HA	1.146	NH	0.556	VA	1.081
ID	0.733	NJ	0.771	WA	1.139
IL	1.159	NM	0.983	WV	1.196
IN	0.740	NY	1.318	WI	0.974
IA	0.745	NC	0.911	WY	0.990
KS	0.765	ND	0.782	PR	0.725
KY	1.888				

a. Source: Derived from FHWA, "Price Trends for Federal-Aid Highway Construction," quarterly.

Chapter 7:

Evaluating Improvements

The HERS model applies a standard benefit-cost framework to the evaluation of improvement alternatives, but "standard" does not mean that the methods are cut-and-dried or necessarily obvious. Considerable distortions or bias can be introduced into the estimation of capital investment requirements by seemingly small errors or misconceptions in how the benefits and costs are discounted and summarized, and in how the BCRs/IBCRs are calculated and used.

This chapter describes the mechanics of how HERS summarizes and discounts benefits, and compares projects against a benefit-cost criterion or against each other. The concepts HERS is implementing are explained in Appendix D, "Basic Theory of Highway Project Evaluation" and Appendix B, "Induced Traffic and Induced Demand."

7.1 Cost and Benefit Calculations

HERS recognizes four broad classes of costs:

- user costs, which are borne by the highway user;
- agency costs, such as maintenance, which are borne by the administrative agency responsible for the section;
- external costs, which are borne by non-users of the highway system (society at large); and
- capital improvement costs.

Benefits are reductions in costs as the result of an improvement, and are measured as the difference in costs between the base case and the improved case (the base case can be either the unimproved section or a less aggressive improvement). When performing benefit-cost analysis, HERS places the first three classes in the "benefit" category, with capital improvement costs being the "costs." Costs that increase as a result of an improvement (i.e., cost savings are negative) are labeled "disbenefits" and added to benefits with a minus sign. An improvement may produce both benefits and disbenefits, as when an improvement that increases average speed brings benefits resulting from the reduction in travel time, and disbenefits from an increase in vehicle operating costs and emissions.

In addition, there is an estimate of benefit from change in consumer surplus resulting from that change in travel that occurs from an improvement that changes the generalized price of travel for the user. This incremental consumer surplus only occurs if demand elasticity is not zero (perfectly inelastic); HERS does not accept elasticities of zero or greater.

Projects are selected using benefit-cost ratios (BCRs), and incremental benefit-cost ratios (IBCRs) relative to a less aggressive improvement alternative. Although the objective is to maximize net benefits (subject to constraints, if any), the procedures use ratios to achieve the goal rather than directly calculating net benefits.

7.1.1 Improvement Selection Procedures

After potential improvements have been identified, HERS evaluates them to gauge their economic attractiveness. HERS makes decisions about improvements on the basis of the ratio of the net present value of each improvement's incremental benefits to the present value of the incremental costs. This ratio is referred to as the incremental benefit-cost ratio, or IBCR. The decisions HERS makes based upon IBCR are:

- Does the section warrant improvement during this funding period?
- If so, which is the economically most attractive improvement for this section?

In a constrained scenario, HERS also asks:

- Among the potential improvements to all sections in the highway system under analysis, which are the economically most attractive?

This chapter first presents the steps HERS uses in determining the benefit-cost ratio (BCR, used interchangeably with IBCR). It then examines how HERS uses the BCR to answer the three questions.

The evaluation process consists of determining the benefit-cost ratio of each candidate improvement. This is accomplished in several steps:

1. identifying the base case;
2. determining the length of the analysis period;
3. determining the user, agency, and external costs associated with the base case;
4. determining the user, agency, and external costs associated with the candidate improvement;
5. determining the capital cost of the improvement;
6. determining the residual value of the improvement; and
7. calculating the benefit-cost ratio.

This chapter addresses the *process* of determining the BCR for candidate improvements. The details of the calculations involved are discussed in Chapter 5, “Estimation of Impacts” (the forecast of traffic volume and pavement condition, and the calculation of user, agency, and external costs), and Chapter 6, “Capital Cost of Improvements”

7.2 The Base Case

In a typical HERS run, when the option to force the model to address unacceptable conditions has not been selected, the initial base case is the unimproved section. That is, the potential benefits of candidate improvements will be compared against the case in which no improvement is made to the section. HERS uses this base case when determining whether a section warrants improvement during the current funding period (see section 7.9, "Does a Section Warrant Improvement?"). However, if the option to force the model to make mandatory improvements to address unacceptable conditions has been selected, HERS uses the mandatory improvement as the base case.

HERS also uses a previously selected improvement as the base case when considering more aggressive improvements. This situation commonly arises in the selection process for constrained runs, and is also used to discover the economically most attractive improvement for a section during a minimum BCR run. Since the differences between the costs and benefits of the two improvements are used in calculating the benefit-cost ratio, the term 'incremental benefit-cost ratio', or IBCR, is often used interchangeably with the term 'benefit-cost ratio'.

7.3 Determining the Benefit-Cost Analysis Period

Generally, when evaluating whether to improve the section during the current funding period, HERS uses a benefit-cost analysis period equal in length to the minimum number of funding periods that will encompass the lifetime of the least aggressive improvement. This might be as little as one or two periods, for example, with a simple resurfacing. The BCA period begins at the midpoint of the current funding period, and extends to the midpoint of the funding period during which the improvement would be "used up" (see Figure 2-8 "HERS Time Periods" on page 2-13).

Table 7-1 provides a brief summary of how the last funding period of a BCA period is determined. Benefit-cost analysis periods consist of an integral number of funding periods, and extend from the mid-point of the funding period in which the improvement is implemented to the midpoint of some subsequent funding period.

Table 7-1. Length of BCA Period

Situation Being Analyzed	Funding Period in Which BCA Period Ends
Section for which no improvement has yet been selected for the current funding period:	
If current funding period is the last one in which resurfacing is practical;	Period in which condition first becomes unacceptable[a], or maximum length of BCAP, or 15 years, whichever occurs first
Otherwise;	Next period in which pavement would "normally" be improved or period in which condition becomes unacceptable[a] after implementing the improvement, or maximum length of BCAP, whichever occurs first
Section for which an improvement has already been selected during the current funding period.	Next period in which pavement would "normally" be improved or period in which condition becomes unacceptable[a] after implementing the already selected improvement, or maximum length of BCAP, whichever occurs first

a. Unacceptable conditions that cannot be corrected (e.g., those that require more widening than is feasible) are excluded from consideration in this test.

In highway management, the improvement question is often viewed not as *whether* a section should be improved, but *when*? In many cases, the two most serious alternatives are "improve during the current funding period" and "improve during the next funding period." HERS does not attempt to optimize over time, and only evaluates whether an improvement might be justified during the current funding period.[1] This is accomplished by comparing it to a "base case" in which no improvement is implemented during the current funding period. Use of such a base case against a simple resurfacing means that the improvement will be made if the benefits of the resurfacing over its lifetime (compared to letting the pavement deteriorate from its existing condition) exceed the costs of the resurfacing. If the improvement fails the BC test, the question of whether to resurface in the next funding period is postponed until that period becomes the current period. When comparing more aggressive improvements to an acceptable initial improvement, the benefits include a residual value from the most aggressive of the two candidates (see section 7.7 below).

7.4 Estimating Variable Costs for the Base Case

After determining the length of the BCA period, HERS calculates the costs associated with the base case for each of the funding periods involved. First (if it has not already been calculated while identifying candidate improvements), HERS predicts the traffic volume (see section 5.6 "The Travel Forecast Model" on page 5-51) and pavement condition (see section 5.1 "The Pavement Deterioration Model" on page 5-1) at the end of the funding period. It then calls upon the routines which calculate the operating costs, travel time costs, safety costs, maintenance costs, and emissions costs. The costs are calculated for the end of the funding period. This process of prediction and cost calculation is repeated for each funding period in the BCA period.

7.5 Determining Costs Associated with the Candidate Improvement

The process of calculating the costs associated with the potential improvement is similar to that for the base case. The model first simulates the effect of the improvement on the section (see section 4.2.4 "Effects of HERS Improvements" on page 4-20). This establishes the pavement condition at the time of the improvement, and HERS applies short-run elasticity to determine the new traffic volume (see section 5.6.3 "The Simultaneous Solution" on page 5-54). Traffic volume and pavement condition are then forecast for the end of the funding period, and the cost calculation routines are called upon to determine the user, agency, and external costs associated with the improved section at that time. The model then repeats the prediction and cost calculation for each funding period in the BCA period.

7.6 Determining the Capital Costs of the Improvements

For most sections being improved, HERS calculates the capital cost by multiplying the cost per lane mile by the number of lanes and by the length of the section. The

1. An analysis of the improve-now-or-later decision criterion is contained in the internal report "Build/NoBuild versus Now/Later" (US DOT/Volpe Center, June 2003). The conclusion is that applying a now-versus-later test produces muddled and misleading results, and adds nothing to the cross-sectional analysis (build-versus-no-build or now-versus-not-now) that HERS conducts.

cost per lane mile depends upon the particular improvement, the section's functional class, and, for rural sections only, the prevailing terrain (flat, rolling, or mountainous). For sections receiving alignment improvements, HERS employs a more complex approach (including the cost of earthwork, clearing and grubbing, pavement, etc.) to determine the cost over the portion of the section being re-aligned. Portions of the section not being re-aligned are costed in the same manner as sections receiving no alignment improvements.

See Chapter 6, "Capital Cost of Improvements" for the detailed presentation of how HERS calculates improvement costs.

7.7 Residual Value

Residual Value is the preferred concept for valuing an improvement after it has passed through its normal lifetime or through some phase of its life. Computation of this value, however, requires information and assumptions that are not currently contained in the HERS model. An expedient is used instead that provides a "refund" of a portion of the project's costs if the analysis period is truncated before the end of the improvement's normal lifetime. This concept is the Remaining Service Life (*RSL)*.

The residual value of an improvement is the capital value remaining at the end of the analysis period. HERS uses *RSL* is a substitute for either residual value or salvage value, although it is not equivalent. Salvage value is applicable if the asset is being terminated and liquidated, which is not usually the case for highway sections. Residual Value (RV) is the capitalized net benefits of the asset in its current use in perpetuity.

The computation of *RSL* is given by the formula:

$$RSL_t = C_0 \times \frac{n \angle t}{n} \qquad \textbf{\textit{Eq. 7.1}}$$

where:

t = length of the benefit-cost analysis period (BCAP);
C_0 = initial cost of the improvement at time *0*;
n = the normal or expected lifetime of the improvement, and $t < n$.

This *RSL* is the value at time t, which must be discounted to time *0* for evaluation of benefits and costs:

$$RSL_0 = RSL_t \times \frac{1}{(1+r)^t} \qquad \textbf{\textit{Eq. 7.2}}$$

where:

RSL_0 = Remaining Service Life in present value terms at time *0*; and
r = discount rate.

7.7.1 Possible Biases From Using *RSL*

The effect of the *RSL* is to give the improvement a "credit" for the unused portion of the investment, scaled proportionately to the percentage of the lifetime that has not already passed. Use of the *RSL* introduces some qualifying considerations to the analysis:

1. If the improvement is worthwhile, benefits after the end of the BCAP are likely to occur at a greater rate per year than the comparable rate that costs would be "spread" over the life of the improvement. Since truncating the analysis period treats these net benefits as zero (i.e., benefits are equal to costs), improvements with long lifetimes suffer a bias against them.
2. Truncating the benefits and rebating a portion of costs yields a different project than the one specified: a shorter lifetime with shorter benefit period, and lower costs. It is likely that such an improvement does not exist, e.g., it is not possible to add half a lane and get whole-lane benefits for half as long.
3. For the *RSL* algorithm to yield reasonable results in HERS, the BCAP must be equal to or less than the life of the shortest-lifetime improvement. If not, the more aggressive alternative is being compared to a base case that has been allowed to deteriorate to unrealistic levels. The proper base case would be repetition of a less aggressive improvement (e.g., resurfacing), until the lifetime of the more aggressive improvement or until the BCAP. HERS does not implement subsequent improvements, so it is necessary that the BCAP be no longer than the lifetime of the least durable improvement being evaluated. As long as more aggressive improvements have longer lifetimes, this condition is satisfied.

7.7.2 An *RSL* Example

In the following numerical example, a more aggressive improvement project (B) is compared to another improvement (A). Both projects are measured against a do-nothing base case. The assumed data are given in Table 7-2. HERS selects the lifetime of the least aggressive improvement as the BCAP.

Table 7-2. Example Improvement Projects

	Project	
	A	B
initial cost (Co)	10	30
constant benefits	5	4
begin benefits (yr)	1	1
lifetime	10	20
analysis period (BCAP)	10	
discount rate	5%	

Diagrammatically, the projects can be represented as shown in Figure 7-1, with the BCAP and project lifetimes indicated.

Benefits and costs for each improvement can be calculated relative to the do-nothing base, with the results shown in Table 7-3. Improvement *A* has no *RSL* because the BCAP coincides with the life of the improvement. The more aggressive improvement

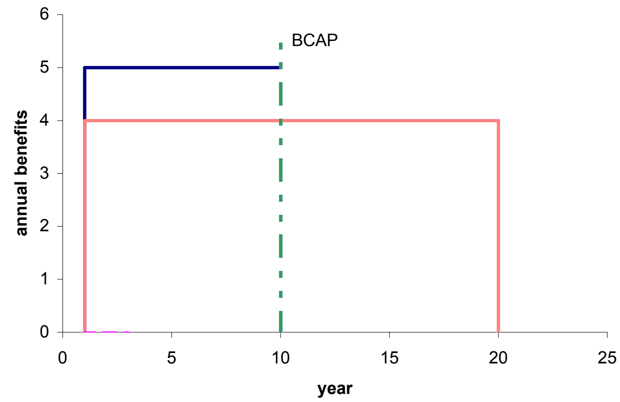

Figure 7-1. Time profile of benefits for two example improvements.

receives a benefit in the form of a share of its initial cost (1/2 in this instance), discounted to year *0*.

Table 7-3. Present value of costs and benefits, including RSL

present worth	fixed BCA period	
costs	10.00	30.00
benefits	38.61	30.89
remaining service life	-	9.21
net benefits	28.61	10.10
BCR	3.86	1.34

7.8 The Benefit-Cost Ratio

The formal HERS benefit-cost ratio, as shown in Equation 7.3 below, compares a base case to a potential improvement. The base case may be the unimproved section or a previously identified improvement, in which case all potential improvements will be more aggressive than the base case improvement. The HERS procedure includes estimation of the incremental costs and benefits of each potential improvement for each period of the benefit-cost analysis period, as well as estimation of the improvement's residual value at the end of the analysis period. The residual value of the improvement is discounted back to the initial year of the analysis period and treated as a benefit of the improvement.

$$IBCR = \frac{(TotCost_B) - (TotCost_I) + RV}{ImpCost_I - ImpCost_B} \qquad \textbf{\textit{Eq. 7.3}}$$

where:

IBCR	=	incremental benefit-cost ratio;
TotCost	=	*Ucost* + *Acost* + *Ecost* for either the base case *B* or the improved case *I*;
UCost	=	user costs (travel time costs, operating costs, and safety costs) for either the base case *B* or the improved case *I;*

ACost	=	agency costs (maintenance costs) for either the base case *B* or the improved case *I;*
ECost	=	external costs (emissions costs) for either the base case *B* or the improved case *I;*
RV	=	residual value of the improvement relative to the base case; and
ImpCost	=	the capital cost of either the base case *B* or the improved case *I*, or zero when the base case is unimproved.

The actual process is slightly more complex. When the benefit-cost analysis period is longer than one funding period in length, benefits must be calculated and accrued for each period. These accruing benefits are then discounted back to the time of implementation.

7.8.1 Consumer Surplus

The introduction of demand elasticity results in different traffic volumes for the base and improved case in each subsequent period. This yields an incremental consumer surplus that must be included in the IBCR calculations for benefit components that are dependent upon VMT (HERS calculates consumer surplus for operating cost benefits, safety benefits, travel time benefits, and user charges that are included in the generalized price; the last portion does not reflect a cost saving but, rather, a willingness to pay for the added or deterred travel).

In Figure 7-1 the base case is represented by the price p_0 and the volume q_0, which intersect on the demand curve. In HERS, the "price" is a generalized price or cost to

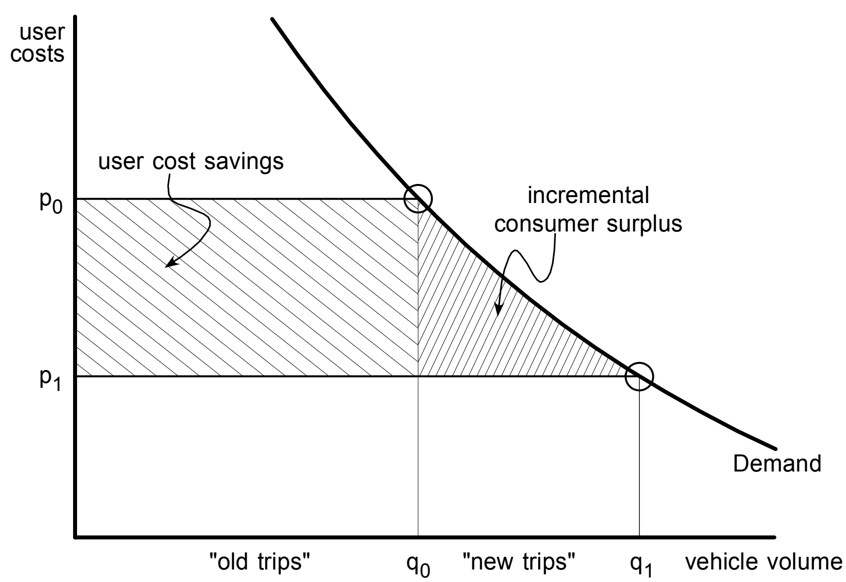

Figure 7-2. User Benefits and Consumer Surplus.

the user that includes travel time, vehicle operating costs, accident risk, and user charges (emissions and agency costs are omitted from the price). The price to the user after improvement is represented by p_I, and results in movement along the demand curve to yield the increased volume q_I. The rectangle labeled “user benefits” represents lower user costs on trips which would have been made had the improvement not changed the price to the user. The triangle labeled “incremental consumer surplus” represents benefits from the additional trips that result from the lower price.

7.8.2 Discounting and Summation

For each funding period, HERS first determines the gross benefit for each of the benefit components: travel time benefits, safety benefits, and operating cost benefits (grouped as user benefits); maintenance cost benefits (agency benefits); and emission cost benefits (external benefits). Maintenance costs are calculated per lane mile; all other components are per vehicle mile traveled. For each of the components, the benefit is:

$$BEN = COST_B \angle COST_I \qquad \textbf{Eq. 7.4}$$

where:

BEN	=	the benefit for a specific cost component;
$COST_B$	=	the base case cost for a specific cost component; and
$COST_I$	=	the improvement case cost for a specific cost component.

HERS also computes a discount factor based upon the user-specified discount rate:

$$DFACTR = DRATE^{(LFP \times (FPC \angle 0.5))} \qquad \textbf{Eq. 7.5}$$

where:

DFACTR	=	discount factor;
DRATE	=	1 + the user-specified discount rate divided by 100;
LFP	=	length of a funding period in years; and
FPC	=	funding period counter pointing to funding period under analysis.

The discount factor is calculated separately for each funding period in the analysis period. HERS next calculates the “per-vehicle” benefit for user and external benefits:

$$BENPV = LFP \times 365 \times SLEN \times (OPBEN + SAFBEN + TTBEN + EMBEN) / DFACTR \qquad \textbf{Eq. 7.6}$$

where:

BENPV	=	discounted benefit per vehicle trip;
SLEN	=	the section length in miles;
OPBEN	=	operating cost benefits per VMT;
SAFBEN	=	safety benefits per VMT;
TTBEN	=	travel time benefit per VMT; and
EMBEN	=	emission cost benefit per VMT.

The interim total in Equation 7.6 includes the discounted benefits for each mile traveled over the section for each day of the funding period for the benefit components expressed by VMT. However, it does not include traffic volume, neither the “old trips”, or the “new trips” which result from the change in user price. HERS calculates the total benefit to include the benefits from “old trips”, the consumer surplus, and the discounted maintenance cost savings:

$$TOTBEN = BENPV \times AADT_B + BENPV \times \frac{AADT_I \angle AADT_B}{2} + MNCBEN / DFACTR \qquad \textbf{Eq. 7.7}$$

where:

TOTBEN	=	discounted total benefits for the funding period;
$AADT_B$	=	AADT for the base case *B;*
$AADT_I$	=	AADT for the improved case *I*; and
MNCBEN	=	maintenance cost benefit for the period.

This total, *TOTBEN*, is calculated for each funding period of the benefit-cost analysis period. When benefits have been calculated for all periods of the benefit-cost analysis period, HERS calculates the IBCR for the improvement:

$$IBCR = \frac{TOTBEN_{SUM} + RV}{(IMPCOST_I \angle IMPCOST_B)} \qquad \textbf{Eq. 7.8}$$

where:

IBCR	=	the incremental benefit-cost ratio for the improvement;
$TOTBEN_{SUM}$	=	the sum of the discounted total benefits for all funding periods in the benefit cost analysis period;
RV	=	the discounted residual value of the improvement;
$IMPCOST_I$	=	the capital cost of the improvement being analyzed; and
$IMPCOST_B$	=	the capital cost of the base case improvement (zero when the base case is “no improvement.”)

7.9 Does a Section Warrant Improvement?

When considering one or more candidate improvements for a section, HERS calculates the BCR for each of them relative to the same base case and for the same evaluation period. When the user has not requested mandatory improvements HERS will decide whether or not the section warrants improvement based upon the highest BCR relative to the unimproved base case. HERS will not improve the section if the highest BCR is less than the qualifying threshold. For constrained runs, the threshold is set at 1.0. For minimum BCR runs, the user specifies the minimum BCR in the specification file (the term “economic efficiency run” is used for a minimum BCR run with a minimum BCR of 1.0).

The case of a section where improvement is not warranted by benefit-cost analysis is shown in Figure 7-3. Three potential improvements have been identified for the section, numbered 10, 20, and 30. The cost of each improvement is shown on the x-axis (shown as c10, c20, and c30), and the benefits of each improvement during the benefit-cost analysis period are plotted on the y-axis (b10, b20, and b30). For each

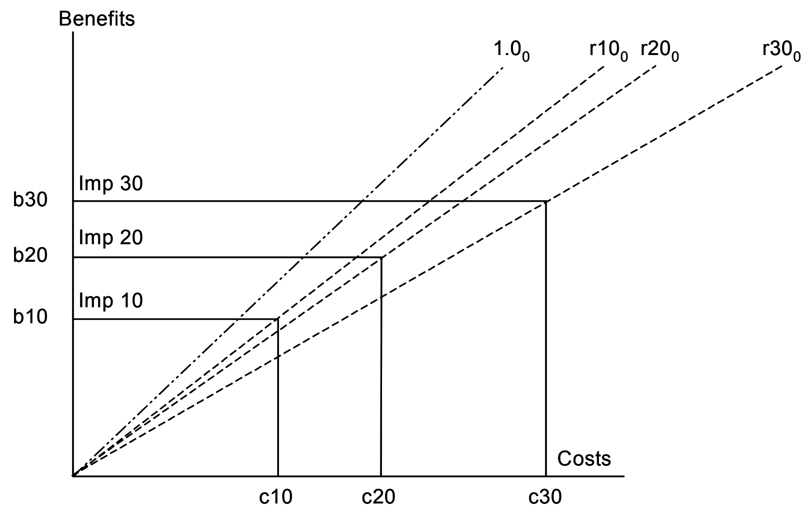

Figure 7-3. Improvement Not Warranted

improvement, a dotted line is drawn from the origin through the intersection of its costs and benefits depicting the improvement's benefit-cost ratio. These are labeled $r10_0$, $r20_0$, and $r30_0$ (the "r" is for ratio, and the subcript zero indicates that the ratio is relative to improvement zero, the unimproved base case). The dashed line drawn at 45° represents a benefit-cost ratio of 1.0. Potential improvement 10 has the highest benefit-cost ratio, as it is closest to 45°; however, as in the other two cases, the potential benefits are less than the capital costs, and the section will not be improved.

Figure 7-4 illustrates the case of a section where two of the potential improvements have benefit-cost ratios greater than 1.0. In this case, potential improvement 10 has the highest benefit-cost ratio. In a minimum BCR run, either improvement 10 or 20 will be implemented; in a constrained run, improvements 10 and 20 will be eligible for implementation.

When the user has specified mandatory improvements, *all* sections for which mandatory improvements have been identified are deemed to justify improvement and—unless the funding limits are reached in a constrained fund run—will be improved. Thus, if improvement 10 in Figure 7-3 were a mandatory improvement, it would be implemented even though its benefit-cost ratio is less than 1.0. A discussion of the selection of more aggressive improvements, including the replacement of mandatory improvements, is contained in the next section.

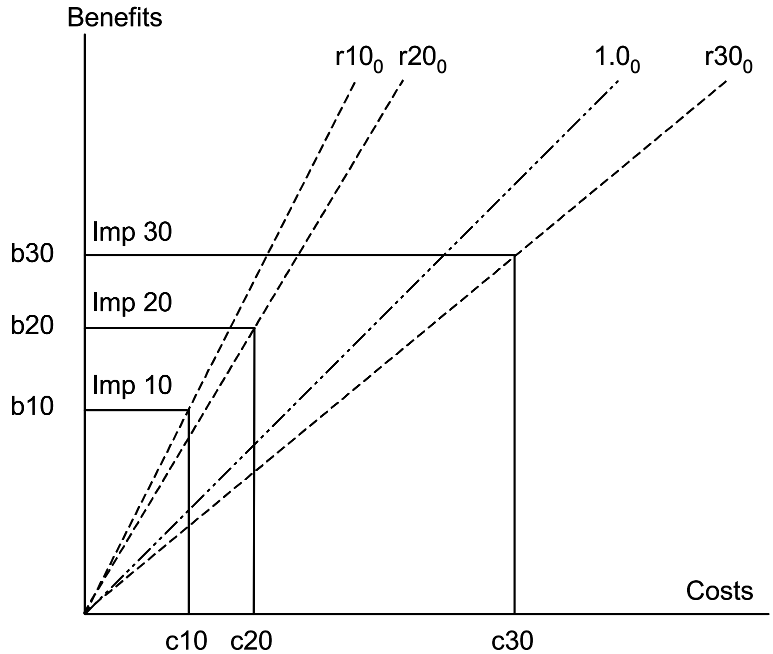

Figure 7-4. Section Warranting Improvement

7.10 Selecting Improvements

As first presented in Chapter 2, "An Outline of the Model Structure" the HERS process has several variants depending upon the analytical objective and whether the user has stipulated that mandatory improvements must be made to correct unacceptable conditions. Previous sections in this chapter presented the steps HERS uses to calculate an improvement's BCR and to determine whether a section warranted improvement during the current funding period. This section examines the HERS methods for deciding which improvement to implement on sections warranting improvement and, during a constrained run, which of the sections warranting improvement will be improved and which will not be improved. The first part of this section examines the process when no mandatory improvements have been specified by the user, first for minimum BCR runs, followed by the process for constrained runs. The second portion of this section contains a discussion of how mandatory improvements are involved in the selection process for each of the three analytical objectives.

7.11 Improvement Selection Without Mandatory Improvements

In most cases, the HERS model is run without the specification of mandatory improvements (this includes runs used in preparation of the 1995, 1997, 1999 and 2002 *C&P Reports*). As shown in Figure 2-4 "HERS Process Flow Without Mandatory Improvements" on page 2-8, HERS uses either of two logic flows when selecting improvements without mandatory improvements. When conducting a minimum BCR analysis, HERS is able to select an improvement for each section immediately after evaluating its potential improvements and determining that it warrants improvement during the current funding period. During a constrained run, HERS “pre-selects” a list of improvements for those sections warranting improvement, and, after processing all sections, selects from that list until the specified constraint has been satisfied. These two processes are presented below in more detail.

7.11.1 Minimum BCR Analysis

When the analytic objective stipulates a minimum BCR run, every section which warrants improvement will be improved. For these sections, then, the question HERS asks is: What is the economically most attractive improvement for this section?

To determine that a section warrants improvement during the current funding period, HERS calculates BCRs for all the potential improvements and identifies the improvement with the highest BCR. This improvement is designated the base case improvement. This base case improvement might not be the most desirable improvement to implement during this period. It may be that an improvement that costs more and generates more benefits is more desirable.

In the example shown in Figure 7-5, the length of the benefit-cost analysis period is set to encompass the life of improvement 10. Of the various options, improvement 20 has the highest initial benefit-cost ratio relative to the unimproved base case: it’s benefit-cost line (labeled “r20”) lies above those for improvements 10 and 30. Improvement 20 has qualified the section for improvement, as its BCR is greater than the minimum threshold of 1.0 (also shown in the figure). Improvements 10 and 30 would also have justified improvement in this funding period. Improvement 20 thus becomes the new base case improvement against which the BCRs of more aggressive improvements will be calculated.

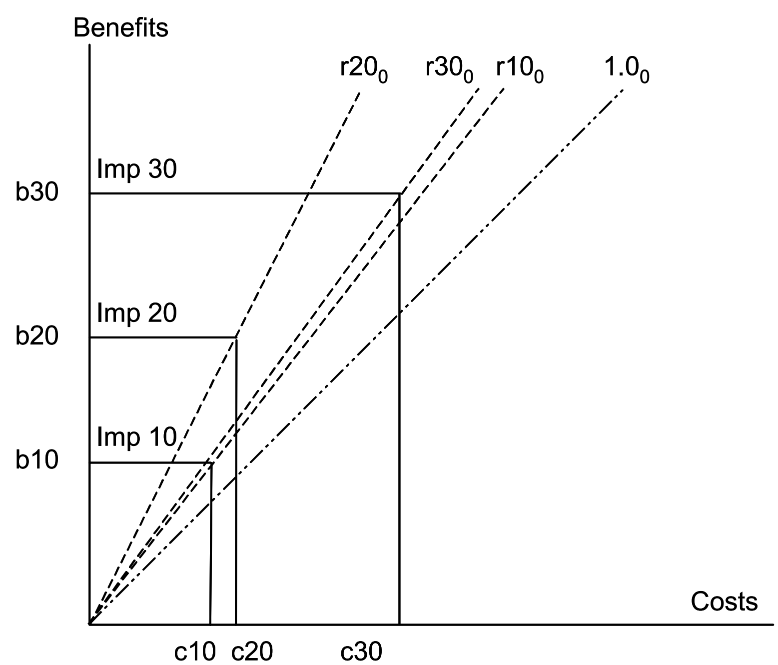

Figure 7-5. Initial Improvement for Minimum BCR Run

To determine whether a more desirable improvement exists, HERS next identifies all more aggressive improvements worth analyzing. HERS numbers improvements in order of increasing aggressiveness; in the example, Improvement 20 is more aggressive than Improvement 10, but less aggressive than Improvement 30. HERS then estimates the incremental benefits and costs of implementing each more aggressive improvement relative to the new base case improvement.

In general, the more aggressive improvement will incorporate some widening and/or alignment option not included in the base case improvement. If this option is not implemented in the current funding period, it is not likely to be implemented until the section is next resurfaced. Accordingly, the incremental benefits and costs of immediately implementing the more aggressive improvement are analyzed over a time frame that ends when the section would normally next be resurfaced following the implementation of the provisionally selected improvement.

The example continues in Figure 7-6. Here, the new base case is improvement 20, so the model calculates an incremental benefit-cost ratio for improvement 30 relative to improvement 20. The length of the benefit-cost analysis period is determined by the life of improvement 20. When the life of improvement 20 is longer than the life of improvement 10, additional benefits accrue to improvement 30 due to the longer period. In the diagram, the increased benefit level for improvement 30 is labeled "$b30_{lp}$" and the recalculated BCR (relative to improvement 20) is labelled "$r30_{lp}$." As the longer-period BCR for improvement 30 is greater than the minimum BCR (MINBCR) specified by the user (the default value is 1.0), improvement 30 will be selected for implementation.

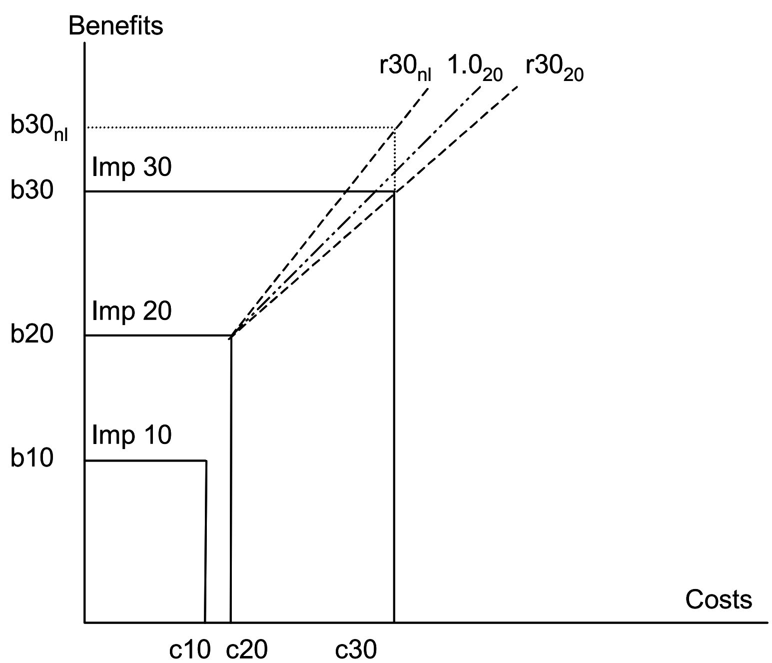

Figure 7-6. Selecting a More Aggressive Improvement

The diagram also shows the BCR for improvement 30 ("r30") calculated without the lengthening of the benefit-cost analysis period. This case would apply when the life of improvements 10 and 20 are the same[1]. This BCR is also greater than MINBCR, with the result that improvement 30 would be selected for implementation. Note that the two BCRs for improvement 30 are drawn as originating from the intersection of improvement 20's costs and benefits. This is because the BCRs are calculated relative to the "base case" of improvement 20. The line representing the minimum BCR threshold of 1.0 also originates from this point.

7.11.2 Constrained Analysis

In a constrained run, whether the constraint is a performance goal or a funding limit, it is possible that not all sections warranting improvement will actually be improved. HERS uses benefit-cost analysis to identify the most attractive set of improvements to meet the analytical objective. If the constraint is a funding limit, the model chooses the set of improvements that will return the greatest net benefit for the capital investment. When the constraint is the attainment of a specified level of highway system performance, the model chooses the set of improvements that will meet the goal with the least expenditure of capital.

Conceptually, the method is easily visualized: calculate BCRs for all possible improvements for all sections, order them by BCR, and select them for implementation in order of economic attractiveness until the constraint/goal is reached. The process is the same for the two types of constraints: the difference is in determining that the constraint has been reached, either (a) all the funds have been expended, or (b) enough improvements have been implemented to satisfy the performance goal.

In practice, HERS uses a 'two-listed' approach which avoids calculating incremental BCRs for more aggressive improvements until they are actually candidates for selection. As with the minimum BCR option, HERS calculates BCRs for all candidate improvements to determine whether the section warrants improvement during the current funding period. Having identified the candidate improvement with the highest initial BCR, that improvement is placed on a list of improvements for potential selection.

Only sections which warrant improvement during the current funding period are represented with an improvement on the potential list. The improvement specified for a section is the one with the highest BCR relative to the unimproved base case. Figure 7-7 diagrams the benefits, costs, and BCRs for three potential improvements to a section. The diagram shows the benefit-cost ratios for improvements 10, 20, and 30, all relative to the unimproved base case (indicated by the subscript 0), as being above the minimum BCR requirement. Of these, the ratio for improvement 10 (labelled "$r10_0$") is the highest; the model will put improvement 10 on the list of potential improvements representing this section.

After HERS has processed all the sections in the highway system, it has a list of potential improvements. Each list entry consists of:

- a section number,
- an improvement number,
- and the improvement's BCR.

1. This case also applies when improvement 10 is selected as the initial improvement.

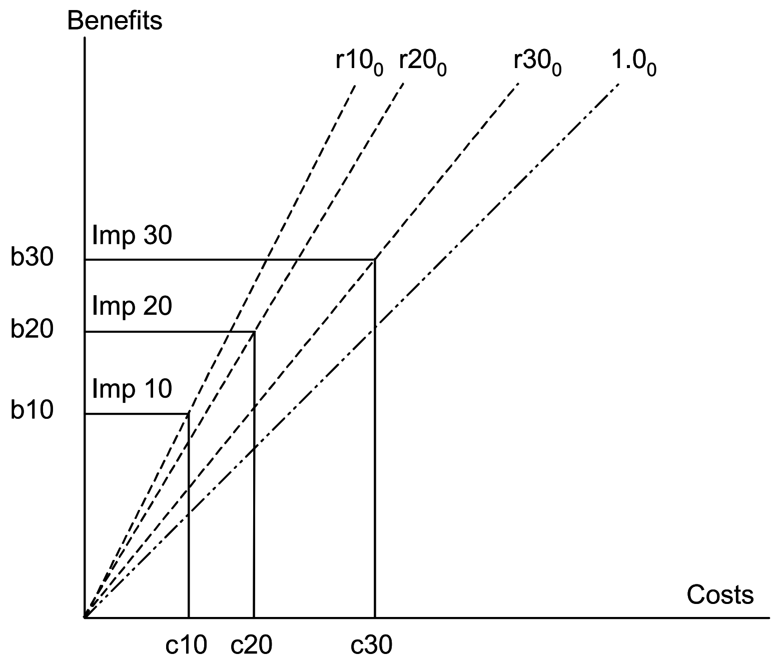

Figure 7-7. Constrained Run: Does Section Warrant Improvement?

The second list, that of selected improvements, is ordered by section number and contains the number of the improvement selected for implementation on the section. If no improvement has been selected for a section, zero is used as the improvement number. Initially, all list entries are set to zero.

HERS proceeds by sorting the potential improvement list by BCR. The list is processed in order of descending BCR. HERS takes the number of the improvement on the top of the potential list and places it on the list of selected improvements. The model then checks whether implementing this improvement violates the funding constraint or satisfies the performance goal.[1]

If not, it examines any more aggressive improvements which may have been identified for the section. HERS calculates incremental BCRs for all more aggressive improvements using a benefit-cost analysis period that corresponds to the life of the base case improvement. The "most recently selected" improvement (the one just moved to the selected list) is used as the base case.

This step is illustrated in Figure 7-8. In this diagram the BCRs for improvements 20 and 30 and the minimum BCR of 1.0 are redrawn to be relative to improvement 10. The length of the benefit-cost analysis period is set to the life of improvement 10 (which was also the time period used in the initial calculations as shown in Figure 7-7). The BCR for improvement 20 is greater than the threshold of 1.0. HERS adds

1. In order to guarantee that net benefits are maximized given the constraint, some special code is required when full implementation of either improvement results in exceeding a funding constraint or a benefits goal. In this situation, the more aggressive improvement is implemented on some of the mileage represented by the sample section, and no improvement is implemented on the remaining mileage; the number of miles to be improved is determined so that the specified objective is just reached.

improvement 20 to the list of potential improvements; its placement on the list depends upon its BCR. For this section, improvement 10 is now entered on the list of selected improvements, and improvement 20 is on the list of potential improvements

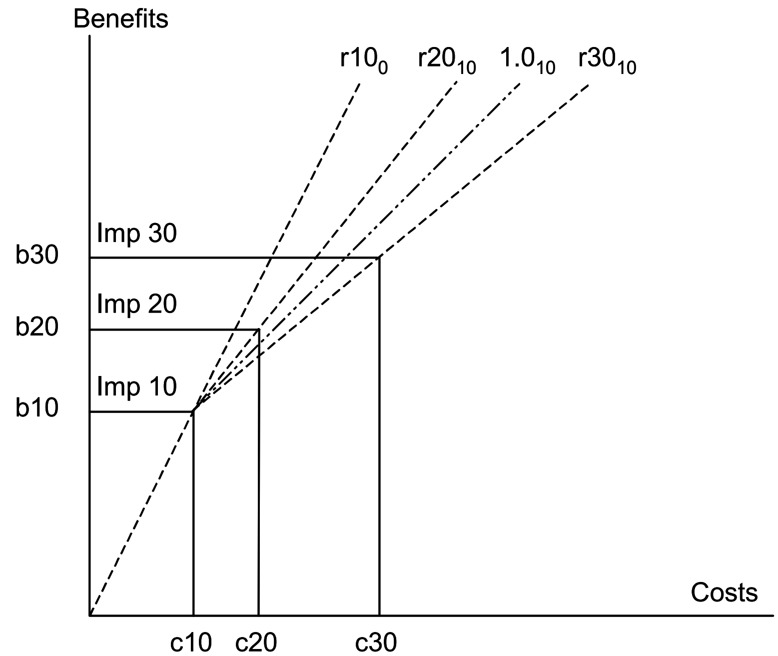

Figure 7-8. Constrained Run: First Check for Aggressive Improvements

The model continues the process of moving improvements from the potential list to the selected list. Should the constraints permit, it will eventually come to the example section's improvement 20 on the potential list. HERS repeats the process, as shown in Figure 7-9.

At this point, improvement 20 represents the most economically attractive improvement option available within the system. HERS moves improvement 20 from the potential list to the selected list and improvement 20 becomes the base case for analyzing subsequent improvements; HERS will now use the expected life of improvement 20 as the length of the benefit-cost analysis period. Figure 7-9 illustrates the case when the life of improvement 20 is the same length as the previously selected improvement. Improvement 30's BCR relative to improvement 20 (represented by "$r30_{20}$") lies below the minimum BCR threshold of 1.0, and therefore it will not be considered a candidate for potental implementation.

It is possible that the expected life of improvement 20 is longer than that of improvement 10. When this is the case, the benefit-cost analysis period (BCAP) for improvement 30 (and other more aggressive improvements, should they exist) is extended to the funding period in which improvement 20 would next be improved. Figure 7-10 presents an illustration of this analysis.

The label "$b30_{20}$" on the Benefits axis represents the additional benefits which accrue to improvement 30 as a result of the extended BCAP. The capital cost of improvement 30 does not change. The additional benefits are sufficient to raise improvement

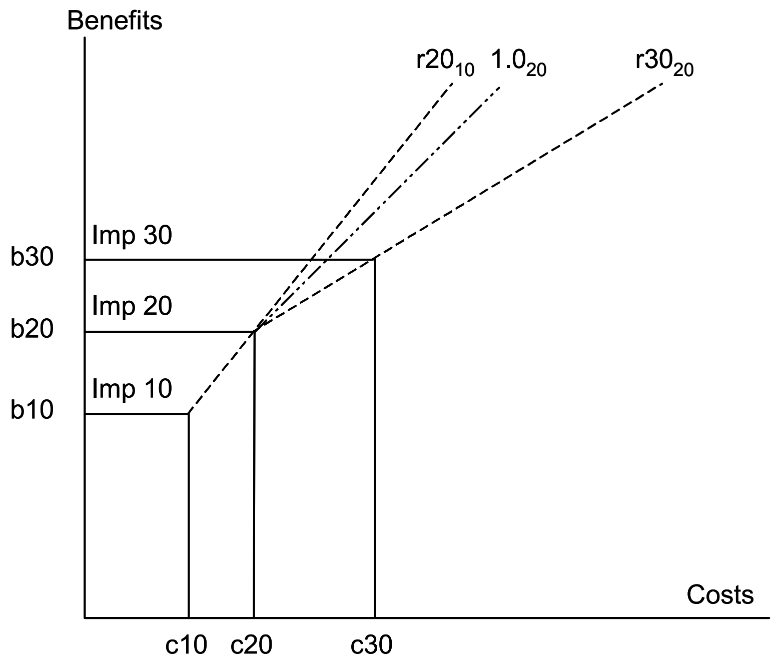

Figure 7-9. Constrained Run: Second Check for Aggressive Improvements

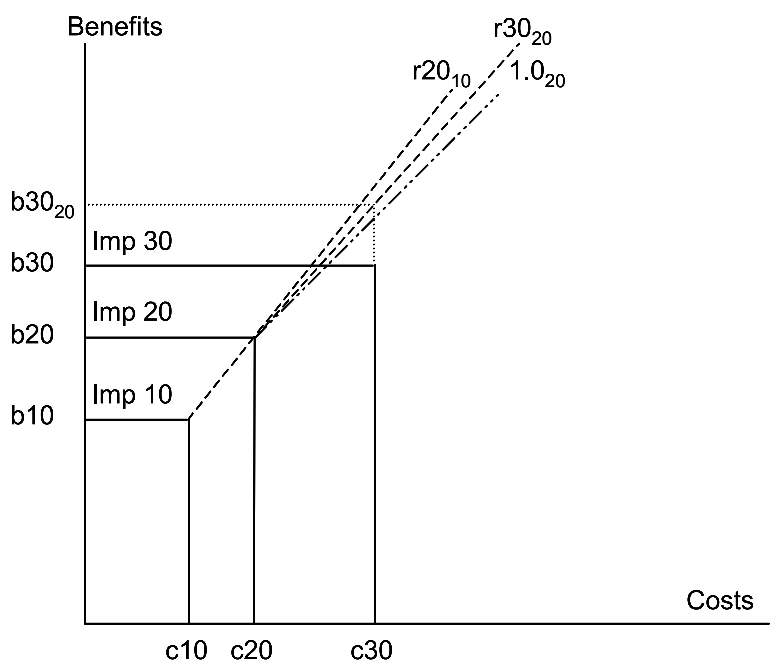

Figure 7-10. Constrained Run: Analysis with Extended BCAP

30's BCR above the 1.0 threshold, so HERS adds improvement 30 to the list of potential improvements, with its placement in the list determined by its BCR. Should the constraints permit, it will be implemented in its turn.

Note that had sufficient additional benefits accrued to improvement 30, its BCR (“$r30_{20}$”) could have exceeded improvement 20’s BCR (“$r20_{10}$”). If this were the case, improvement 30 would immediately supplant improvement 20 on the list of selected improvements, thus skipping the potential list entirely.

7.12 Selecting Mandatory Improvements

The HERS process for identifying mandatory improvements is presented in section 4.2.3.5 “Addressing Unacceptable Conditions: the Optional First Pass” on page 4-15. Typically, all mandatory improvements will be selected for implementation. The two exceptions are when there are insufficient funds to implement all mandatory improvements (this applies to fund-constrained runs only), and when a selected mandatory improvement is replaced by a more aggressive improvement.

When a mandatory improvement has been identified for a section during the first processing pass, it is subsequently identified as the base case improvement during analysis of more aggressive improvements (when mandatory improvements are not being considered, the unimproved case is used as the base case). This may result in the implementation of an improvement with a BCR below the usual threshold of 1.0. While this may seem anomalous in an economic model, the mandatory improvement feature is provided to allow the user to ensure that highways in unacceptably poor condition are improved regardless of whether the improvements can be justified economically.

Figure 7-11 presents an example. During the initial pass, improvement 10 was selected as a mandatory improvement for the section. As a mandatory improvement, its BCR (designated r10) does not have to meet a minimum threshold. Improvement 20 was identified during the second pass, and its incremental BCR (shown as $r20_{10}$) was calculated using improvement 10 as the base case with the length of the analysis period set to the life of improvement 10.

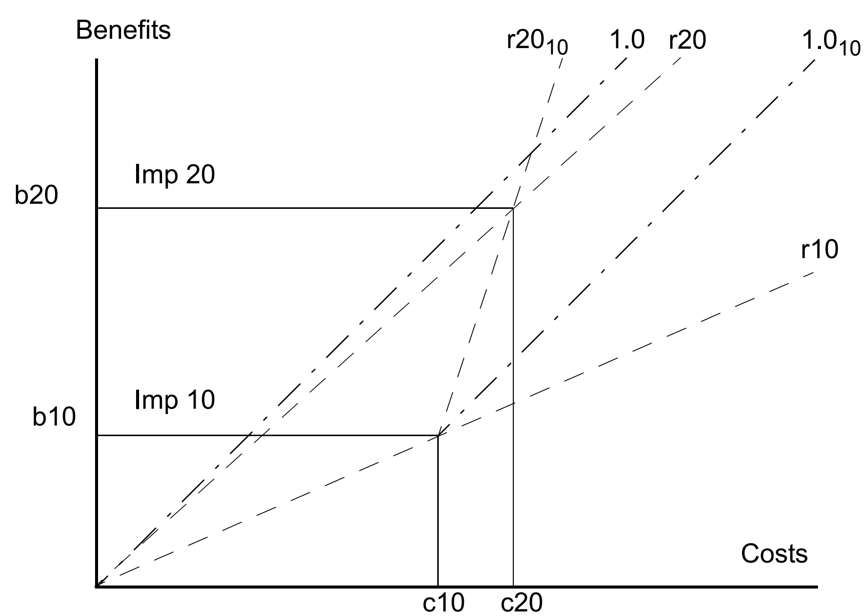

Figure 7-11. Replacement of a Mandatory Improvement

While improvement 20 is certainly more attractive than the mandatory improvement 10 (r20 lies above r10), neither would have been selected had the user not specified the correction of unacceptable conditions, as both of their BCRs are less than 1.0 relative to an unimproved base case (both r10 and r20 lie below the threshold designated 1.0.). Because the mandatory improvement 10 was used as the base case, however, the model calculates improvement 20's BCR relative to improvement 10, shown in Figure 7-11 as $r20_{10}$. This BCR lies above the threshold 1.0_{10}, which is relative to improvement 10. The model therefore replaces improvement 10 with improvement 20.

The case illustrated represents a possibility which can occur in both constrained and minimum BCR runs when mandatory improvements are specified, and results from the use of the mandatory improvement as the base case. Note that the objective of the mandatory improvement of unacceptable conditions is still achieved: unacceptable conditions are corrected. And while the replacement improvement (improvement 20 in the example) is not in itself attractive, it is an economically more attractive improvement than the one it replaces.

7.12.1 Unacceptable Conditions and the Constrained Fund Run

During a constrained fund run, HERS uses benefit-cost analysis to select among potential improvements until the available funds are expended. The user electing to have unacceptable conditions identified and corrected during a constrained fund run will designate a portion of the total funds for this purpose. If the designated funds are sufficient to implement all mandatory improvements identified in the first pass, the remaining funds are available for the correction of other deficiencies during the second pass.

If the designated funds are insufficient, then benefit-cost analysis is used to select the most economically attractive of the mandatory improvements for implementation. The procedure used is the same as presented above for constrained runs (see section 7.11.2), except that the universe of potential improvements consists only of the mandatory improvements identified during the first pass through the sections. Those mandatory improvements not selected at this point are placed on the list of potential improvements and will be evaluated for implementation during the second pass, competing (on the basis of their relative BCR values) with non-mandatory improvements for the non-reserved funds.

During the second pass, improvements selected as mandatory may be replaced by a more aggressive improvement on that section if it presents a more economically attractive alternative.

It is important to consider carefully the designation of funds for the correction of unacceptable conditions. Consider the case where, during the initial funding period of a run, a large number of unacceptable conditions may be identified, and funds remaining for use during the second pass may be very limited. In the case of a section with two deficiencies, including one that is unacceptable, only the unacceptable deficiency would be corrected during the initial funding period. The other deficiency would frequently be corrected with a separate improvement selected during a subsequent funding period - an inefficient means of correcting the two deficiencies. For this reason, when the option of correcting unacceptable conditions is exercised, it is desirable that at least some funds be reserved in each period for implementing more aggressive improvements. HERS allows the user to specify either (a) specific funding levels for the correction of unacceptable conditions, or (b) a maximum percentage of available funds that can be allocated for mandatory improvements for each combination of functional classes during any funding period (see section 2.10, "Functional Classes," page 2-13, for the combinations of functional classes recognized by HERS).

7.12.2 Unacceptable Conditions and the Performance Constrained Run

During a performance constrained run, HERS uses benefit-cost analysis to select among potential improvements until designated system performance levels are met. The user may either specify explicit levels of performance or require that the program maintain the current level of system performance. If the user selects to have unacceptable conditions identified and corrected during such a run, the program executes the first loop to identify sections with unacceptable conditions and improvements for their correction. If implementing all such improvements would improve the system beyond the specified level, all the mandatory improvements are implemented, and no more aggressive improvements are identified. In this case, unlike the constrained fund run, HERS does not use benefit-cost analysis to select the smallest (and most economically attractive) set of mandatory improvements which meet the specified goal.

Should the implementation of all identified improvements not bring the system performance level to the desired goal, the second pass procedures are exercised to identify deficiencies and improvements. As in the case of the Constrained Fund run, a more aggressive improvement may be selected to replace an improvement originally selected to correct an unacceptable condition.

7.12.3 Unacceptable Conditions and the Minimum BCR Run

During a minimum BCR run, HERS evaluates potential improvements for all deficient sections and selects the most aggressive improvement with an incremental BCR above the user-specified minimum. If the user opts to have unacceptable conditions identified and corrected during such a run, the program executes the first loop to identify sections with unacceptable conditions and improvements for their correction. The model then executes the second loop to identify improvements to correct "normal" deficiencies and to identify more aggressive improvements.

Each section found to be in unacceptable condition by the first processing loop will be improved, either with the improvement which corrects the unacceptable condition or by a more aggressive improvement. In this case, as with constrained runs, improvements originally selected to correct unacceptable conditions are implemented regardless of their BCR unless superseded by a more aggressive improvement. As depicted in Figure 7-11, the more aggressive improvement which replaces a mandatory improvement may not in itself have qualified for implementation had its incremental BCR not been calculated against the mandatory improvement.

As in a minimum BCR run in which the option to correct unacceptable conditions was not exercised, economically attractive improvements from the second processing loop will be implemented if their incremental BCRs are above the specified threshold.

7.13 User-Specified Improvements

This section details how HERS-ST estimates the user benefits and improvement costs of user-specified improvements and also the corresponding incremental benefits and incremental costs of replacing a user-specified improvement by a more aggressive improvement.

7.13.1 Improvement Costs

If the cost of any user-specified improvement is provided, HERS-ST uses that cost as the cost of the improvement. Otherwise, if the improvement is a HERS-type improvement, the cost is estimated using the HERS-ST procedure for estimating improvement costs. If no cost is provided for a special improvement, HERS-ST prints a warning message and sets the improvement cost to a default value.

When evaluating the possibility of replacing a HERS-type user-specified improvement (e.g., resurfacing, as identified by a State's Pavement Management System) by a more aggressive improvement (e.g., resurface and add lanes), HERS-ST estimates the incremental cost of replacing the former improvement by the latter one. This incremental cost is estimated as the difference between estimates of the costs of the two improvements that are both obtained using HERS' procedure for estimating improvement costs (regardless of whether the user has provided an exogenous cost estimate for the user-specified improvement).

Consider the possibility of replacing a non-HERS-type user-specified improvement (Type divisible by 20) by a combination of that improvement and a HERS-type of improvement. The cost of the combined improvement is estimated by using the HERS-ST procedure for estimating improvement costs to estimate the cost of the HERS-type of improvement, and adding this cost to the cost of the original user-specified improvement. Thus, the resulting estimate of the incremental cost of adding the HERS-type improvement ignores any efficiencies obtained by implementing both improvements simultaneously; and so there may be a tendency to overestimate the incremental cost.

If the first improvement applies only to an intersection or interchange and the second applies to an entire section, this effect is likely to be fairly small and so may be ignored. However, if both improvements apply to the entire section, the effect may be more significant. For this reason, HERS-ST will tend to overestimate the incremental cost of adding a HERS-type improvement to a user-specified improvement that affects an entire section. Also for this reason, HERS-ST requires that the override flag be set to one for user-specified improvements that combine HERS-type and non-HERS-type improvements.

7.13.2 User Benefits

HERS-ST estimates the user benefits of an improvement as the net reduction in user costs resulting from changes in the physical characteristics of the improved section (including increases in the number of lanes) and from the resulting increases in capacity and average speed.

In the case of user-specified improvements, the user specifies any increase in the number of lanes and any increase in capacity of the section. The user benefits of a non-HERS-type improvement (Type divisible by 20) are estimated entirely from these two increases. For such improvements, if both fields are zero, estimated benefits will be zero. (However, if only the second field is zero, increased capacity will be estimated from the increase in the number of lanes.)

User-specified improvements that either are purely HERS-type (Type < 20) or are a combination of HERS-type and non-HERS-type (Type not divisible by 20), may produce other changes in the physical characteristics of the section. These are simulated by HERS-ST, and thus they provide another potential source of information for estimating user benefits. For these sections, the estimates of user benefits reflect any non-capacity effects of these changes plus either the user-coded change in capacity or, if the capacity change is not coded, the HERS-ST estimate of change in capacity.

When evaluating the possibility of replacing a user-specified improvement by a more aggressive improvement, HERS-ST estimates the incremental user benefits of the replacement by analyzing the effects of the replacement on the physical characteristics of the section and the resulting effects on user benefits. This process is straightforward when the capacity effects of the user-specified improvement are not supplied by the user (but calculated by HERS-ST), but it requires some clarification for the case in which the user specifies these effects. In the latter case, HERS-ST distinguishes several different estimates of capacity:

1. Estimated capacity before implementation of the user-specified improvement.
2. Estimated capacity after implementation of this improvement - obtained by adding the user-coded capacity effect of the improvement to **[1]**.
3. A separate estimate of capacity after implementation of the improvement that is produced by HERS-ST entirely from the physical characteristics of the section after improvement (ignoring the user-coded capacity effect).
4. HERS-ST's estimate of capacity after implementation of the more aggressive improvement (obtained entirely from the physical characteristics of the section without reference to the user-specified capacity effect of the original improvement).

The benefits of the replacement are then estimated by using **[2]** as estimated capacity without the replacement, and **[2]** + **[4]** - **[3]** as estimated capacity with the replacement.

Chapter 8:

Model Output

The HERS model produces an extensive variety of statistics describing the forecast state of the highway system, the costs and benefits of the implemented improvements, and the history of each section. This chapter describes the three forms of output produced by HERS: the printable text file, the comma-delimited system statistics files, and the comma-delimited section output files.

The HERS-ST GUI provides an array of tools for the manipulation of this output data and the creation of reports, charts, and maps. See the *HERS-ST User's Guide* for further information.

8.1 Printed Output

HERS outputs a text file, suitable for printing, that summarizes the overall system conditions and improvements selected by the model. Certain of the pages are optional and can be suppressed through settings in the RUNSPEC.DAT file. If all pages are requested, HERS will output 169 pages. The printable output consists of the following:

1. One page of output summarizing the state of the system at the start of the run;
2. For each funding period, one page of output summarizing the state of the system at the end of the funding period;
3. For each funding period and for the overall analysis period, one page of output summarizing how the system is forecast to change between the beginning and the end of the period; and
4. For each funding period and for the overall analysis period, many pages of additional output providing information on the costs and benefits associated with the selected improvements.

The output pages are presented in four layout formats, as discussed below. HERS places the printable output in a single text file named by the user in the specification file (RUNSPEC.DAT). Two of these formats are also available in comma-delimited layout.

8.1.1 The System Conditions Output Format

HERS uses this format for items one through three in the above list of output pages. In addition to the run number and run description information from the RUNSPEC file, this page contains the following information for each of the nine functional systems in the HERS database, with individually produced summary forecasts for the rural system, the urban system, and for the complete system:

1. Miles in the system;
2. Average PSR (paved sections only);
3. Average IRI (inches per mile, paved sections only);
4. Average speed;
5. Congestion Delay (hours per 1000 vehicle-miles);
6. Total Delay (hours per 1000 vehicle-miles);
7. Total VMT;
8. Travel-time costs (dollars per thousand vehicle-miles);
9. Operating costs, listed for all vehicles combined and separately for four-tire vehicles and for trucks (dollars per thousand vehicle-miles);
10. Crash costs (dollars per thousand vehicle-miles);
11. Total user costs, which is a summation of travel-time costs, operating costs for all vehicles, and crash costs (dollars per thousand vehicle-miles);
12. Number of crashes (per 100 million vehicle miles);
13. Number of injuries (per 100 million vehicle miles);
14. Number of fatalities (per 100 million vehicle miles);
15. Annual maintenance costs (dollars per mile);
16. Average cost of pollution damage (dollars per 1000 vehicle-miles); and
17. Percent of total VMT on roads not meeting the user specified thresholds.

The user may specify condition thresholds for the following properties:

- pavement condition (PSR);
- peak-hour volume/capacity ratio;
- lane width;
- right-shoulder width;
- shoulder type;
- surface type;
- horizontal alignment; and
- vertical alignment.

The initial page of output in this format presents the conditions at the beginning of the analysis period. It also includes the date and time the run was executed, the number of center-line miles, and the number of sections in the sample.

For each funding period, HERS produces a page of output summarizing conditions at the end of the period. This is followed by a page summarizing the changes in conditions which occurred during the funding period. This second page of output also shows the (incremental) benefit-cost ratio of the last improvement selected. If a constraint was placed on available funds, this page also displays the amount of funds spent; while, if a performance goal was specified, it compares the performance level achieved with the specified goal.

HERS produces a similar summary of the change in conditions during the overall analysis period.

8.1.2 The Deficiency Summary Output Format

These pages, four for each funding period plus four for the overall period, provide a detailed picture of the deficiencies present on the system and the effectiveness of improvements in reducing the deficiencies. The pages are presented in pairs: the first page lists the deficiencies as percent of vehicle miles travelled; the second lists the deficiencies as a percentage of center-line miles. These pages include data for all sections in the system whether improved or not.

For the first funding period, a pair of pages describes system deficiencies at the start of the overall analysis period. Then, and for each subsequent funding period, two pairs of pages describe deficiencies at the end of the period, and changes in deficiencies during the funding period. Finally, a pair of pages describes changes in deficiencies over the entire analysis period.

The format provides statistics for nine deficiencies by functional class with rural, urban, and overall totals. Each deficiency is measured at a minimum of three levels, as presented in Table 8-1. HERS uses deficiency levels from the DLTBLS.DAT input file. While many of the levels are the same as those used in evaluating section deficiencies for possible improvement, others are specified solely for the purpose of accumulating these output statistics. HERS labels these levels as *USTn*, where *UST* represents “User Specified Threshold” and *n* distinguishes between multiple levels.

Table 8-1. Deficiency Levels in Output

Deficiency	Threshold Operation	Levels
IRI	% above specified threshold	UST1 - User specified threshold 1
		UST2 - User specified threshold 2
		UST3 - User specified threshold 3
		UST4 - User specified threshold 4
		UST5 - User specified threshold 5
PSR	% below specified threshold	UL - Unacceptable level
		RL - Reconstruction level
		DL - Deficiency level
		UST1 - User specified threshold 1
		UST2 - User specified threshold 2
V/C Ratio	% above specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1
		WS - Widening standard
Lane Width	% below specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1
Shoulder Width	% below specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1
Shoulder Type	% below specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1
Surface Type	% below specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1
Horizontal Alignment	% below specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1
Vertical Alignment	% below specified threshold	UL - Unacceptable level
		DL - Deficiency level
		UST1 - User specified threshold 1

8.1.3 The "By Improvement Type" Output Format

HERS produces the bulk of each funding period's pages of printable output in this format. Each page contains a pair of tables: the upper table contains statistics for all sections improved during the funding period, while the lower table contains statistics for only those sections whose improvements included re-aligning all or a portion of the section. Statistics for sections included in the lower table are also included in the upper.

These pages do not include statistics on or derived from sections not improved during the funding period.

This format is organized by functional class versus improvement type. The lowest level of reporting is for a particular improvement type on a specific functional class (for example, statistics regarding resurfacing with shoulder improvements on rural major collectors). The user selects which pages are to be included in the printable output via switches in the RUNSPEC file. A subset of these pages are also available for the overall analysis period, as noted in the paragraphs below.

Generally, for sections with lanes added at high cost, all statistics for that section are tabulated as if all the added lanes were added at high cost. This is done even for those sections in which some lanes are added at normal cost while others are added at high cost. (The cost of adding the lanes is calculated to use different improvement costs -- see Chapter 6.) The exception is the Lane-miles Added output page.

8.1.3.1 The Total Initial Cost of Selected Improvements

This page summarizes the capital cost of all implemented improvements. For each section being improved, HERS first determines the cost per mile as detailed in Chapter 6. HERS then multiplies the cost by the section length (SLEN) and the expansion factor (EXPFAC) to calculate the full cost of the improvement. HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly.

This page is also available for the overall analysis period.

8.1.3.2 Initial Cost of Preservation Improvements

This page enumerates the amount of capital investment HERS specified for the preservation of existing highways. This includes all the funds used for the reconstruction, resurfacing, alignment improvement, and shoulder improvements of existing lanes. For details, see section 6.5, "Allocating Capacity and Preservation Costs," page 6-8.

This page is also available for the overall analysis period.

8.1.3.3 Initial Cost of Capacity Improvements

This page lists the capital investment HERS allocated to the expansion of capacity. It includes the cost of adding lanes and the incremental cost of widening existing lanes. For details, see section 6.5, "Allocating Capacity and Preservation Costs," page 6-8.

This page is also available for the overall analysis period.

8.1.3.4 Lane-miles Improved

This page summarizes the lane-miles improved. For each section being improved, HERS determines the lane-miles as the number of through lanes (*TLANES* after improvement) multiplied by the section length (*SLEN*) and the expansion factor (*EXPFAC*). HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly.

This page is also available for the overall analysis period.

8.1.3.5 Lane-miles of Mandatory Improvements Selected on a Priority Basis To Address Unacceptable Conditions

This page summarizes the lane-miles improved only on sections where the improvement was implemented to correct an unacceptable condition. As discussed in paragraph 4.2.3.5, the criteria for selecting these improvements are the correction of extremely poor highway conditions, and these improvements are not subjected to the benefit-cost test. (In HERS, statistics pertaining to mandatory improvements selected to address unacceptable conditions are collected only for improvements that are not replaced by a more aggressive non-mandatory improvement selected on the basis of its benefit-cost ratio.) The calculation of lane-miles is the same as above: the number of through lanes (TLANES after improvement) multiplied by the section length (SLEN) and the expansion factor (EXPFAC). HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly. The mileage shown on this page is included in the Lane-miles Improved page.

This page is also available for the overall analysis period.

8.1.3.6 Lane-miles of Non-mandatory Improvements Not Selected on a Priority Basis

This page summarizes the lane-miles improved only on sections where the improvement was not implemented to correct an unacceptable condition. For a model run where the user did not stipulate mandatory improvements, this page presents the same data as the Lane-miles Improved page. If mandatory improvements are stipulated, this page presents the differences between the Lane-miles Improved page and the Lane-miles of Mandatory Improvements page. (That is, the values on this page added to their corresponding values on the Lane-miles of Mandatory Improvements page will equal those on the Lane-Miles Improved page -- with some small differences due to rounding.) For each section being improved, HERS determines the lane-miles as the number of through lanes (TLANES after improvement) multiplied by the section length (SLEN) and the expansion factor (EXPFAC). HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly.

This page is also available for the overall analysis period.

8.1.3.7 The Net Present Value of the Residual Value of All Improvements

[This would be changed to “NPV of RSL” except that we’re not doing the page at all now in the National baseline as of December 2003.]

8.1.3.8 The Average Benefit-Cost Ratio of Selected Improvements

This page presents the average BCRs for all implemented improvements. The BCRs reported are calculated against the unimproved base case for each section over an analysis period determined by the methodology explicated in paragraph 7.3. The average BCRs are weighted by improvement cost.

This page is also available for the overall analysis period.

8.1.3.9 Total Benefits in the Last Year Of The Period

On this page HERS totals user benefits (travel time savings, operating cost savings, and safety benefits) and maintenance cost savings during the last year of the period. Benefits due to savings in emissions costs are not included on this page.

8.1.3.10 Maintenance Costs Savings in the Last Year Of The Period

The HERS procedure for estimating pavement maintenance costs (see paragraph 5.7) is based upon the deterioration of pavement from an initial PSR to a final PSR without regard to the time period involved. When estimating the savings in maintenance costs on an improved section at the end of the current funding period, HERS uses the difference between the end-of-period maintenance costs of the improved and unimproved instances of the section. HERS calculates these values based upon the decline in PSR between the middle of the first and second funding periods; that is, during the initial benefit-cost analysis period (BCAP; see section 2.9, “HERS Time Frames,” page 2-13). HERS assumes that maintenance costs increase linearly during the

BCAP, and that the middle year of the BCAP (which is the last year of the funding period) incurs the average cost (that is, one-fifth of the costs of a five year period).

The maintenance costs are stored as dollars per center-line mile. To calculate the maintenance cost savings in the last year of the funding period, HERS subtracts the maintenance cost for that year after improvement from the maintenance cost for that year before improvement. The savings is expanded by multiplying by the section length (SLEN) and the expansion factor (EXPFAC).

8.1.3.11 User Benefits in the Last Year Of The Period

This page totals the benefits to users of implemented improvements. User benefits include travel time savings, operating cost savings, and safety benefits (which in turn includes the cost of fatalities, injuries, and property damage). The totals on this page will equal the sum of their corresponding entries on those pages (allowing for differences due to rounding).

8.1.3.12 Travel Time Savings in the Last Year Of The Period

This page summarizes the monetarized savings to highway users due to reductions in time spent travelling on improved sections. The (per-section) savings are calculated as the difference between the travel time costs without improvement less the travel time costs following improvement:

$$TTS = (TTC_u - TTC_i) \times AVMT_u + \frac{(TTC_u - TTC_i) \times (AVMT_i - AVMT_u)}{2} \qquad \textbf{\textit{Eq. 8.1}}$$

where

TTS	=	travel time savings on the section;
TTC_n	=	travel time cost in dollars per vehicle mile on the unimproved section *u* or the improved section *i* (see paragraph 5.5, "Travel Time Costs"); and
$AVMT_n$	=	annual VMT (daily volume × section length × expansion factor × 365) for unimproved section *u* or improved section *i*.

The pavement condition, traffic volume, speed, and costs are calculated for the end of the funding period in which the improvement was implemented, and the calculations include consumer surplus. HERS totals the per-section travel time savings by functional class and improvement type.

8.1.3.13 Operating Cost Savings in the Last Year Of The Period

This page summarizes the operating cost savings to highway users after improving a section. HERS includes fuel consumption; oil consumption; tire wear; maintenance and repair; and vehicle depreciation as operating costs. The (per-section) savings are calculated as the difference between the operating costs without improvement less the operating costs following improvement:

$$OCS = (OC_u - OC_i) \times AVMT_u + \frac{(OC_u - OC_i) \times (AVMT_i - AVMT_u)}{2} \qquad \textbf{\textit{Eq. 8.2}}$$

where

OCS	=	operating cost savings on the section;

OC_n	=	operating cost cost in dollars per vehicle mile on the unimproved section *u* or the improved section *i* (see paragraph 5.2, "Estimating Operating Costs"); and
$AVMT_n$	=	annual VMT (daily volume × section length × expansion factor × 365) for unimproved section *u* or improved section *i*.

The pavement condition, traffic volume, speed, and costs are calculated at the end of the funding period in which the improvement was implemented, and the calculations include consumer surplus. HERS sums the operating cost savings by improvement type and functional class.

8.1.3.14 Safety Benefits in the Last Year Of The Period

This page summarizes monetarized safety benefits to highway users after improving a section. As safety costs HERS includes the cost of fatalities; the cost of injuries; and the cost of property damage. HERS computes the (per-section) benefits as the difference between the safety costs without improvement less the safety costs following improvement:

$$SB = (SC_u \angle SC_i) \times AVMT_u + \frac{(SC_u \angle SC_i) \times (AVMT_i \angle AVMT_u)}{2} \quad \textbf{\textit{Eq. 8.3}}$$

where

SB	=	safety benefits on the section;
SC_n	=	safety costs in dollars per vehicle mile on the unimproved section *u* or the improved section *i* (see paragraph 5.3, "Safety Costs"); and
$AVMT_n$	=	annual VMT (daily volume × section length × expansion factor × 365) for unimproved section *u* or improved section *i*.

HERS calculates the pavement condition, traffic volume, speed, and costs at the end of the funding period in which the improvement was implemented, and the calculations include consumer surplus. HERS sums the operating cost savings by improvement type and functional class.

8.1.3.15 Crashes Avoided in the Last Year Of The Period

On this page HERS lists the number of crashes avoided in the last year of the funding period on improved sections. The data does not include information on sections which HERS did not improve during the funding period.

8.1.3.16 Injuries Avoided in the Last Year Of The Period

This page summarizes the number of injuries avoided in the last year of the funding period on improved sections. Only sections HERS improved during the funding period are included in the totals.

8.1.3.17 Lives Saved in the Last Year Of The Period

On this page HERS totals the number of lives saved in the last year of the funding period on improved sections. HERS does not include data from unimproved sections.

8.1.3.18 VMT For Improved Sections in the Last Year Of The Period

This page totals the annual vehicle miles travelled on improved sections during the last year of the funding period.

8.1.3.19 Emissions Costs Savings in the Last Year of the Period

This page tabulates the emission cost savings on improved sections during the last year of the funding period. HERS calculates the savings on a section as:

$$EMCBen = (EMC_u \angle EMC_i) \times VMT_u \angle EMC_i \times (VMT_i \angle VMT_u) \qquad \textbf{Eq. 8.4}$$

where:

$EMCBen$	=	emission cost savings;
EMC_n	=	emission cost per vehicle mile of travel on the unimproved section *u* or the improved section *i* (see paragraph 5.8, ”External Costs” for details);
VMT_n	=	vehicle miles traveled in the last year of the funding period on the unimproved section *u* or the improved section *i*.

Note that HERS regards the cost of emissions on additional trips on the section (as a result of a lower user price due to the improvement) as a disbenefit, and subtracts it from benefits realized through the reduction of emissions on existing trips.

8.1.3.20 Miles Improved

This page summarizes the center-line miles improved. For each section being improved, HERS calculates the center-line miles as the section length (SLEN) multiplied by the expansion factor (EXPFAC). HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly.

8.1.3.21 Miles of Mandatory Improvements Selected on a Priority Basis To Address Unacceptable Conditions

This page tabulates the center-line miles improved only on sections where the improvement was implemented to correct an unacceptable condition. As discussed in paragraph 4.2.3.5, the criteria for selecting these improvements are the correction of extremely poor highway conditions, and these improvements are not subjected to the benefit-cost test. (In HERS, statistics pertaining to mandatory improvements selected to address unacceptable conditions are collected only for improvements that are not replaced by a more aggressive non-mandatory improvement selected on the basis of its benefit-cost ratio.) The calculation of center-line miles is: the section length (SLEN) multiplied by the expansion factor (EXPFAC). HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly. The mileage shown on this page is included in the Miles Improved page.

8.1.3.22 Miles of Non-mandatory Improvements Not Selected on a Priority Basis

This page totals the center-line miles improved only on sections where the improvement was not implemented to correct an unacceptable condition. For a model run where the user did not stipulate mandatory improvements, this page presents the same data as the Miles Improved page. If mandatory improvements are stipulated, this page presents the differences between the Miles Improved page and the Miles of Mandatory Improvements page. (That is, the values on this page added to their corresponding values on the Miles of Mandatory Improvements page will equal those on the Miles Improved page -- with some small differences due to rounding.) For each section being improved, HERS determines the center-line miles as the section length (SLEN) multiplied by the expansion factor (EXPFAC). HERS categorizes the datum by the improvement type and functional class and accumulates it accordingly.

8.1.3.23 Lane-miles Added to the System through Widening Improvements

This page summarizes the lane-miles added to the system as a result of improvements which add lanes. It does not include mileage from widening existing lanes.

Because only four improvement types result in added lane miles, the format of this page is abbreviated: the improvement types which do not add lanes are not included in the format. This page also departs from the usual practice in that it allocates the lane-miles added between high and normal cost based upon the status of the individual lanes. For example, consider a section that was resurfaced and had four lanes added, two at normal and two at high cost. The HERS improvement type is “Major Widening with High Cost Lanes,” and the statistics for the section (costs, miles improved, last year of period) are grouped with other sections of the same improvement type. On the Lane-miles Added page, however, HERS allocates the added lane-miles evenly between the Major Widening with High Cost Lanes and Major Widening with Average Cost Lanes categories.

8.1.4 The “By IBCR” Output Format

HERS produces up to four printable summary sets in this format.[1] The data is organized by functional class versus improvement type, and, within each improvement type, by incremental BCR range. Therefore, where the “by improvement type” format might show that HERS identified 4.542 billion dollars of resurfacing improvements for rural major arterials, the “by IBCR” format could show that 1.261 billion dollars were invested in improvements with BCRs greater than or equal to 6.0. HERS uses the following BCR ranges:

- 1.0-1.2;
- 1.2 - 2.0;
- 2.0 - 3.0;
- 3.0 - 4.0;
- 4.0 - 5.0;
- 5.0 - 6.0; and
- >= 6.0

The four summary sets are:

1. Capital requirements (initial cost);
2. Number of sample sections improved (including duplicates);
3. Miles improved; and
4. Travel time benefits expressed as a percentage of total user benefits.

There is no comma-delimited output in this format.

8.2 Comma-Delimited Files

The HERS-ST GUI makes extensive use of the comma-delimited files, loading the output into databases for use in generating user-customizable outputs. HERS-ST generates the two files in formats which mimic the Systems Conditions Output pages and the By Improvement Type output pages.

1. For this format, to refer to “pages” would be somewhat misleading, as each summary set requires more than two physical pages to print.

For the Systems Conditions Output pages, HERS creates an output file named [*RUN-NUM*].SS1 (where the file name is the same as the run number entry in the RUN-SPEC file) which contains the comma-delimited version of this format. HERS generates a "page" for the initial system conditions and the conditions at the end of each funding period. Each page contains only the sixteen data items listed above (i.e., not the number of center-line miles, sections in the sample, etc.).

For the By Improvement Type pages, HERS creates the file [*RUNNUM*].SS2 to hold the comma-delimited output for selected pages of output using this format. The comma-delimited format includes only the "all improvements" set of statistics: it does not include the data for improvements with improved alignment. (That is, it only includes the top half of each output page.) The comma-delimited output set contains per funding period and overall analysis period statistics for the following pages:

- initial cost of selected improvements;
- initial cost of preservation improvements;
- initial cost of capacity improvements;
- lane-miles improved;
- miles improved;
- lane-mile added; and
- the average benefit-cost ratios of selected improvements.

8.3 Section Output Files

In addition to the conventional HERS output, for each funding period (FP), HERS-ST produces a comma-delimited ASCII file describing the condition of each section at the end of the FP along with information about all improvements that have been selected and the effects of these improvements. The file describing conditions at the end of FP *nn* is called SECNS*nn*.OUT. The first record of the file contains the final year of the FP. The second contains the user's description of the run. The third record contains a set of column headings shown in Table 8-2; and the remaining records contain descriptions of all sections, in comma-delimited format, as listed in Table 8-2 and described below.

The first data item in each record contains the record number of the HPMS file containing the original description of the section. This number may be useful in locating the record.

Items 2 - 7 contain additional identification of the section being improved. These items are obtained from the corresponding HPMS record.

Items 8 - 14 identify deficiencies that will exist by the end of the FP if the section is not improved. Four of these items (PSR, lane width, shoulder type, and right shoulder width) correspond to items in the HPMS file. Volume/capacity (v/c) ratio (Item 8) is HERS' estimate of the ratio of design-hour volume to peak-period hourly capacity. Horizontal and vertical alignment adequacy (Items 12 and 13) are either derived from information supplied on curves and grades by class, or they are obtained from the

Table 8-2. Record Format and Column Headings of SECNSnn.OUT Files

Field	Column Heading	Data Type
Section Identification		
1. Record number	RECNO	Integer
2. County code	CNTY	Integer
3. Section identification	SECID	Character
4. Sample identifier	SAMPID	Character
5. LRS identification	LRSID	Character
6. LRS beginning point	BEGMP	Floating Point
7. LRS ending point	ENDMP	Floating Point
Deficiencies		
8. PSR	PSR0	Floating Point
9. Volume/Capacity ratio	VCR0	Floating Point
10. Lane width	LW0	Integer
11. Shoulder type	SHLT0	Integer
12. Right shoulder width	RSHLW0	Integer
13. Horizontal alignment adequacy	HORA0	Integer
14. Vertical alignment adequacy	VERA0	Integer
Improvement		
15. Improvement type	ITYPE	Integer
16. Lanes added	LADD	Integer
17. Increase in capacity	CAPINC	Floating Point
18. Type of selection	TYPSEL	Integer
19. BCR	BCR	Floating Point
Characteristics at End of FP		
20. Volume/Capacity ratio	VCR	Floating Point
21. Average speed	SPD	Floating Point
22. PSR	PSR	Floating Point
23. IRI (inches/mile)	IRI	Floating Point
24. Total lanes	TLAN	Integer
25. Peak lanes, peak direction	PLAN	Integer
26. Peak lanes, opposite direction	CPLAN	Integer
27. Peak capacity, peak direction	PCAP	Floating Point
28. Peak capacity, opposite direction	CPCAP	Floating Point
29. Off-peak capacity	OPCAP	Floating Point
30. Access control	ACCESS	Integer
31. Lane width	LWID	Integer

Table 8-2. Record Format and Column Headings of SECNSnn.OUT Files

32. Shoulder type	SHLT	Integer
33. Right shoulder width	RSHLW	Integer
34. Median type	MEDT	Integer
35. Median width	MEDW	Integer
36. Widening feasibility	WFEAS	Integer
37. Horizontal alignment adequacy	HORA	Integer
38. Vertical alignment adequacy	VERA	Integer
39. AADT	AADT	Floating Point
40. Emissions costs	EMC	Floating Point
Costs and Benefits		
41. Improvement cost	IMPC	Floating Point
42. Emissions benefits	EMB	Floating Point
43. Travel-time benefits	TTB	Floating Point
44. Operating-cost benefits	OPCB	Floating Point
45. Safety benefits	SAFB	Floating Point
46. Total benefits	TOTB	Floating Point
State Control Field		
47. State control field	SCF	Character

input values for horizontal and vertical alignment adequacy. In both cases, they use the HPMS codes for alignment adequacy. A simplified description of these codes[2] is:

1. All curves (or grades) meet design standards.
2. Some curves (or grades) do not meet design standards, but they do not affect speed or safety.
3. Infrequent curves (or grades) affect speed or safety.
4. Several curves (or grades) affect speed or safety.

The next five items (15 through 19) describe the improvement that is finally selected for the section, if any. If one or more potential improvements are identified but none are selected, these items describe the rejected improvement with the highest BCR. If no potential improvement is evaluated in this FP, these items are blank. The use of these items when an improvement is selected is described below:

- *Improvement type*. A code identifying the type of improvement. The codes used for the improvement types that can be generated in basic runs are shown in the last two columns of Table 8-3. As discussed in section 4.1 "The Override Mode and User-Specified Improvements" on page 4-1, in override runs, the HERS-ST user may introduce additional codes to represent other types of (user-specified) improvements. The improvement types shown in Table 8-3

2. More formal descriptions of the alignment adequacy codes are contained in FHWA, *Highway Performance Monitoring System Field Manual*, December 1999, pp. IV-31 and IV-32.

are the only ones analyzed by the National HERS system. In section 4.1 "The Override Mode and User-Specified Improvements" on page 4-1, these improvement types are referred to as "HERS-type" improvements.

Table 8-3. Codes for "HERS-Type" Improvements

IMPRCOST Code		Improvement Code: Without Alignment Improvement	Improvement Code: With Alignment Improvement
Rs	Resurface	1	11
RsSh	Resurface and improve shoulders	2	12
MinW	Resurface and widen lanes (minor widening)	3	13
MWNC	Resurface and add normal-cost lanes (major widening)	4	14
MWHC	Resurface and add high-cost lanes	5	15
RC	Pavement reconstruction	6	16
RCWL	Pavement reconstruction with wider lanes	7	17
RCNC	Pavement reconstruction and add normal-cost lanes	8	18
RCHC	Pavement reconstruction and add high-cost lanes	9	19

- *Lanes added* is the number of lanes added by the improvement (if any).
- *Increase in capacity.* The increase in peak-period peak-direction capacity (if any) produced by this improvement.
- *Type of selection*. This field identifies the roles played by HERS-ST and the user in the improvement selection process. Table 8-4 presents the codes used by HERS-ST. (It should be noted that HERS-ST produces information about some improvements that were *not* selected.)
- *BCR*. Normally, the BCR of the improvement is the discounted present value (at the time of improvement implementation) of the sum of the user and agency benefits of the improvement divided by the implementation costs. An exception occurs when the system is operating under a funding constraint or with a performance goal (i.e., when objective type is 1 or 2) and two (or more) alternative improvements are provisionally selected for a section in sequence. In this case, the BCR of the improvement is an *incremental* BCR; i.e., it is derived from the incremental benefits and costs of choosing the improvement that is finally selected to replace the last previous improvement that had been provisionally selected.

The next 21 items describe the section at the end of the FP. Items 22 - 25, 27, 30 - 36, and 39 correspond to items in the HPMS file. Items 20, 37, and 38 correspond to Items 9, 13, and 14 of the SECNS*nn* file and are described above. Items 21 and 40 are the program's estimates of: the overall average speed on the section (in mph); and the external costs of emissions in the last year of the FP generated by vehicles using the section (in thousands of dollars). Item 39 is HERS' estimate of AADT at the end of the FP.

Table 8-4. Type of Selection Codes

Code	Interpretation
1	Improvement was evaluated by HERS-ST but not selected.
2	Improvement was selected by HERS-ST.
3	Improvement was specified by user. (User requested HERS-ST *not* to add additional options).
4	Improvement was requested by user; HERS-ST did not find any cost-effective options to add.
5	Improvement combines options requested by user with options added by HERS.
6	Improvement combines a HERS-ST selection for this FP with a Table 8-3 Type1, 2, or 6 improvement requested by the user for a subsequent FP.

Item 26 is the number of "counter-peak" lanes; i.e., the number of peak-period lanes in the "non-peak" direction. This value is usually obtained by subtracting the number of peak lanes in the peak direction (Item 25) from the total number of (off-peak) through lanes (Item 24). However, for some sections, HERS infers the likely existence of extra peak-period lanes resulting from parking restrictions or use of shoulders as travel lanes during the peak period. For these sections, total peak lanes (Items 25 and 26) will exceed (off-peak) through lanes (Item 24). For rural sections with less than four lanes, "peak" lanes represent the total number of lanes in both directions, and counter-peak lanes equals zero.

Corresponding to peak, counter-peak, and through lanes are three values of capacity: peak, counter-peak, and off-peak capacity (Items 27 - 29). For rural roads with less than four lanes, the peak and off-peak capacities are two-way capacity, and counter-peak capacity is zero. For all other roads, the three capacities are one-way capacities. Peak capacity is the capacity coded in the HPMS record. Off-peak and counter-peak capacities may be equal to or smaller than peak capacity.

The next part of the record contains information about the costs and benefits of any improvement. The first of these fields contains improvement costs (in thousands of dollars) supplied by the user (see section 3.1.2, "User-Specified Improvements Data File," page 3-4) and/or estimated by the program (see Chapter 6; for special considerations regarding the cost calculations of improvements which combine a user-specified improvement with a HERS improvement, see section 4.1.3.1, "Improvement Costs," page 4-5).

When section-specific estimates of improvement costs for a specific improvement are supplied by the user, these costs are used for that improvement. If the program chooses to combine this improvement with an additional widening option and/or an alignment improvement, the *incremental* cost of these options are estimated and added to the total.

The next five fields are the program's estimates of the user and external benefits of the improvement in the last year of the FP, in thousands of dollars. Separate estimates are provided of the benefits of reductions in emissions costs, travel time, operating costs, and crash costs, along with the sum of all four types of benefits. Negative values in the fields for emissions benefits or safety benefits indicate an estimated *increase* in emissions or safety costs. For improvements that are estimated by the program to result in increased use of the section, estimated benefits include the benefits to new users of the section (estimated per new vehicle to equal half the per-vehicle benefits to old users). If no potential improvement is evaluated in the FP, these fields are blank.

The final field of the record reproduces the contents of the State Control Field (Field 8 of the HPMS record).

The system user may find it useful to read the SECNSnn.OUT files into Excel. Attempting to open any of these files in Excel results in entering Excel's Text Import Wizard. After entering this subsystem, the user should choose "Delimited" in Step 1, and choose only "Comma" in Step 2. In Step 3, the Format should be set to "Text" for Columns 3 - 5 and 47[3] and left as "General" for all other columns.[4] The imported file will contain: the final year of the FP on Line 1; the user's description of the run on Line 2; and a set of column headings (from Table 8-2) on Line 3. To adjust all spreadsheet columns to the appropriate widths, the user should highlight the entire spreadsheet except Rows 1 and 2 and then ask Excel to select the appropriate column widths (Format, Column, AutoFit Selection).

The HERS-ST GUI also provides advanced tools for the viewing, sorting, and presentation of this data.

3. Scrolling down two lines will cause Columns 1 - 6 to appear in the Data Preview. Column 47 can be reached by scrolling to the right.
4. The Text Import Wizard can be bypassed by changing the file type to CSV before reading the file into Excel. This alternative is simpler, but it assigns "General" format to all columns. If Columns 3, 4, or 46 have any cells that contain only numeric characters, "General" format will result in interpreting the contents of these cells as numbers, an interpretation that may not always be desirable.

Appendix A:

Default Deficiency Criteria Tables

Suggested default values for the ULs, SDLs, and DLs for the eight section characteristics are presented in Table A-5, and Table A-7 through Table A-11 (These values were used in processing for the 2002 *C&P Report*). As indicated in the exhibits, for rural sections HERS allows separate values to be specified for three terrain types and eight combinations of functional system and average daily traffic (AADT). For urban sections, HERS allows separate values for each of five functional systems.

In the case of pavement condition (Table A-1, "Default Pavement Condition Criteria (PSR)"), SDLs are not shown, but a set of "reconstruction levels" (RLs) are. SDLs for pavement condition are not needed because all improvements involve either resurfacing or reconstruction, and, in HERS, only one of these two improvement options are considered for a section in any funding period. The pavement option considered is resurfacing unless PSR is below the RL or certain surface-type deficiencies (specified in Figure 4-2 "Identification of Aggressive Pavement Option" on page 4-12) exist.[1]

Tables A-5 through Table A-9 also show the User Specified Thresholds (USTs) and, in several of the tables, the design standards (DS) for rural sections used by HERS. Table A-2, "Default Pavement Condition Thresholds (IRI)," consists entirely of USTs. The design standards used for median width and for curves and grades are shown in Table A-10, "Default Design Standards For Median Width (Feet)," and Table A-11, "Default Design Standards For Curves and Grades." The design standards used for urban sections are shown in Table A-12, "Default Design Standards for Urban Sections."

The USTs are not used by HERS in selecting improvements; however the shoulder type USTs are used as design standards when shoulders are improved and the lane width USTs are used to specify the lane width following reconstruction of an unpaved section. HERS uses the USTs to develop some summary statistics.

1. For medium and high-type pavement, PSR is the sole determinant of whether a section should be reconstructed; and for low-type pavement, it is the primary determinant. HERS is unable to take into account other influences on the reconstruction decision (e.g., height of the pavement crown), because they are not currently described in the HPMS database.

Table A-1. Default Pavement Condition Criteria (PSR)

UL	RL	UST1	UST2	DL			
					Rural:		
1.8	2.3	1.0	3.0	3.2		Interstate:	Flat
1.8	2.3	1.0	3.0	3.2			Rolling
1.8	2.3	1.0	3.0	3.2			Mountainous
1.8	2.3	1.0	3.0	3.2		OPA AADT>6000:	Flat
1.8	2.3	1.0	3.0	3.2			Rolling
1.8	2.3	1.0	3.0	3.2			Mountainous
1.5	2.3	1.0	2.8	3.0		OPA AADT<=6000:	Flat
1.5	2.3	1.0	2.8	3.0			Rolling
1.5	2.3	1.0	2.8	3.0			Mountainous
1.2	2.0	1.0	2.4	2.6		MA AADT>2000:	Flat
1.2	2.0	1.0	2.4	2.6			Rolling
1.2	2.0	1.0	2.4	2.6			Mountainous
1.2	2.0	1.0	2.4	2.6		MA AADT<=2000:	Flat
1.2	2.0	1.0	2.4	2.6			Rolling
1.2	2.0	1.0	2.4	2.6			Mountainous
1.0	1.5	1.0	2.0	2.4		Coll.'s AADT>1000:	Flat
1.0	1.5	1.0	2.0	2.4			Rolling
1.0	1.5	1.0	2.0	2.4			Mountainous
0.8	1.5	1.0	2.0	2.4		Coll.'s AADT=400-1000:	Flat
0.8	1.5	1.0	2.0	2.4			Rolling
0.8	1.5	1.0	2.0	2.4			Mountainous
0.6	1.5	1.0	1.8	2.2		Coll.'s AADT<400:	Flat
0.6	1.5	1.0	1.8	2.2			Rolling
0.6	1.5	1.0	1.8	2.2			Mountainous
					Urban:		
2.0	2.3	1.0	3.2	3.4		Interstate	
1.8	2.3	1.0	3.0	3.2		Other Freeway & Expressway	
1.6	2.3	1.0	2.8	3.0		Other Principal Arterial	
1.0	2.0	1.0	2.4	2.6		Minor Arterial	
0.8	1.5	1.0	2.0	2.4		Collector	

Table A-2. Default Pavement Condition Thresholds (IRI)

UST1	UST2	UST3	UST4	UST5			
					Rural:		
268.9	241.1	134.4	95.0	170.0		Interstate:	Flat
268.9	241.1	134.4	95.0	170.0			Rolling
268.9	241.1	134.4	95.0	170.0			Mountainous
268.9	241.1	134.4	95.0	170.0		OPA AADT>6000:	Flat
268.9	241.1	134.4	95.0	170.0			Rolling
268.9	241.1	134.4	95.0	170.0			Mountainous
316.8	241.1	152.6	95.0	170.0		OPA AADT<=6000:	Flat
316.8	241.1	152.6	95.0	170.0			Rolling
316.8	241.1	152.6	95.0	170.0			Mountainous
375.6	316.8	193.1	95.0	170.0		MA AADT>2000:	Flat
375.6	316.8	193.1	95.0	170.0			Rolling
375.6	316.8	193.1	95.0	170.0			Mountainous
375.6	316.8	193.1	95.0	170.0		MA AADT<=2000:	Flat
375.6	316.8	193.1	95.0	170.0			Rolling
375.6	316.8	193.1	95.0	170.0			Mountainous
423.5	398.5	241.1	95.0	170.0		Coll.'s AADT>1000:	Flat
423.5	398.5	241.1	95.0	170.0			Rolling
423.5	398.5	241.1	95.0	170.0			Mountainous
482.3	398.5	241.1	95.0	170.0		Coll.'s AADT=400-1000:	Flat
482.3	398.5	241.1	95.0	170.0			Rolling
482.3	398.5	241.1	95.0	170.0			Mountainous
558.0	482.3	268.9	95.0	170.0		Coll.'s AADT<400:	Flat
558.0	482.3	268.9	95.0	170.0			Rolling
558.0	482.3	268.9	95.0	170.0			Mountainous
					Urban:		
241.1	216.0	117.4	95.0	170.0		Interstate	
268.9	241.1	134.4	95.0	170.0		Other Freeway & Expressway	
299.9	268.9	152.6	95.0	170.0		Other Principal Arterial	
423.5	398.5	193.1	95.0	170.0		Minor Arterial	
482.3	423.5	241.1	95.0	170.0		Collector	

Table A-3. Default Surface Type Criteria and Standards[a]

UL	SDL	UST1	DL	DS[b]			
					Rural:		
2	2	2	2	2[c]		Interstate:	Flat
2	2	2	2	2			Rolling
2	2	2	2	2			Mountainous
2	2	2	2	2		OPA AADT>6000:	Flat
2	2	2	2	2			Rolling
2	2	2	2	2			Mountainous
3	3	2	2	2		OPA AADT<=6000:	Flat
3	3	2	2	2			Rolling
3	3	2	2	2			Mountainous
3	3	3	3	2		MA AADT>2000:	Flat
3	3	3	3	2			Rolling
3	3	3	3	2			Mountainous
4	4	3	3	3		MA AADT<=2000:	Flat
4	4	3	3	3			Rolling
4	4	3	3	3			Mountainous
4	4	3	3	3		Coll.'s AADT>1000:	Flat
4	4	3	3	3			Rolling
4	4	3	3	3			Mountainous
4	4	4	4	4		Coll.'s AADT=400-1000:	Flat
4	4	4	4	4			Rolling
4	4	4	4	4			Mountainous
5	5	5	5	4		Coll.'s AADT<400:	Flat
5	5	5	5	4			Rolling
5	5	5	5	4			Mountainous
					Urban:		
2	2	2	2			Interstate	
2	2	2	2			Other Freeway & Expressway	
3	3	2	2			Other Principal Arterial	
4	4	3	3			Minor Arterial	
5	5	4	4			Collectors	

a. Surface Type Codes: 1 = High flexible; 2 = High rigid; 3 = Intermediate; 4 = Low; 5 = Unpaved.

b. HERS does not allow design standard of 5 (unpaved), substituting 4 if a standard of 5 is specified.

c. Design standard is high type. HERS actually uses flexible pavement for all resurfacing and for reconstruction of flexible pavements; rigid pavement is used for reconstruction of rigid and composite pavements

Table A-4. Default Volume/Capacity Ratio Criteria

UL	SDL	UST1	DL	WS			
					Rural:		
0.90	0.85	0.80	0.70	0.70		Interstate:	Flat
0.95	0.90	0.80	0.80	0.80			Rolling
0.98	0.95	0.80	0.90	0.90			Mountainous
0.90	0.85	0.80	0.70	0.70		OPA AADT>6000:	Flat
0.95	0.90	0.80	0.80	0.80			Rolling
0.98	0.95	0.80	0.90	0.90			Mountainous
0.90	0.85	0.80	0.70	0.70		OPA AADT<=6000:	Flat
0.95	0.90	0.80	0.80	0.80			Rolling
0.98	0.95	0.80	0.90	0.90			Mountainous
0.90	0.85	0.80	0.70	0.70		MA AADT>2000:	Flat
0.95	0.90	0.80	0.80	0.80			Rolling
0.98	0.95	0.80	0.90	0.90			Mountainous
0.90	0.85	0.80	0.70	0.70		MA AADT<=2000:	Flat
0.95	0.90	0.80	0.80	0.80			Rolling
0.98	0.95	0.80	0.90	0.90			Mountainous
0.90	0.85	0.80	0.70	0.70		Coll.'s AADT>1000:	Flat
0.95	0.90	0.80	0.80	0.80			Rolling
0.98	0.95	0.80	0.90	0.90			Mountainous
1.00	1.00	0.80	0.95	0.95		Coll.'s AADT=400-1000:	Flat
1.00	1.00	0.80	0.95	0.95			Rolling
1.00	1.00	0.80	0.95	0.95			Mountainous
1.00	1.00	0.80	1.00	1.00		Coll.'s AADT<400:	Flat
1.00	1.00	0.80	1.00	1.00			Rolling
1.00	1.00	0.80	1.00	1.00			Mountainous
					Urban:		
0.98	0.95	0.80	0.90	0.90		Interstate	
0.98	0.95	0.80	0.90	0.90		Other Freeway	
0.98	0.95	0.80	0.90	0.90		Other Principal Arterial	
0.98	0.95	0.80	0.90	0.90		Minor Arterial	
0.98	0.95	0.80	0.90	0.90		Collectors	

Table A-5. Default Lane Width Criteria and Standards (Feet)[a]

UL	SDL	UST1	DL	DS			
					Rural:		
11	11	12	12	12		Interstate:	Flat
11	11	12	12	12			Rolling
11	11	12	12	12			Mountainous
10	11	11	12	12		OPA AADT>6000:	Flat
10	11	11	12	12			Rolling
10	11	11	12	12			Mountainous
10	11	11	12	12		OPA AADT<=6000:	Flat
10	11	11	12	12			Rolling
10	11	11	12	12			Mountainous
8	9	10	12	12		MA AADT>2000:	Flat
8	9	10	12	12			Rolling
8	9	10	12	12			Mountainous
8	9	10	12	12		MA AADT<=2000:	Flat
8	9	10	12	12			Rolling
8	9	10	12	12			Mountainous
8	9	10	12	12		Coll.'s AADT>1000:	Flat
8	9	10	12	12			Rolling
8	9	10	12	12			Mountainous
8	8	8	11	11		Coll.'s AADT=400-1000:	Flat
8	8	8	11	11			Rolling
8	8	8	11	11			Mountainous
8	8	8	10	10		Coll.'s AADT<400[b]:	Flat
8	8	8	10	10			Rolling
8	8	8	10	10			Mountainous
					Urban:		
11	11	12	12			Interstate	
10	11	11	12			Other Freeway	
9	10	10	12			Other Princ. Arterial	
8	8	8	12			Minor Arterial	
8	8	8	12			Collectors	

a. For sections for which the database contains roadway width instead of lane width, HERS treats lane width as one-half the roadway width.

b. For unpaved collectors in this volume category, HERS applies these criteria to the sum of lane width and shoulder width.

Table A-6. Default Right-Shoulder Width Criteria and Standards (Feet)

UL	SDL	UST1	DL	DS			
					Rural:		
6	7	8	10	12		Interstate:	Flat
6	7	8	9	10			Rolling
6	6	6	7	8			Mountainous
6	7	8	9	10		OPA AADT>6000:	Flat
6	7	8	9	10			Rolling
6	6	6	7	8			Mountainous
6	7	8	9	10		OPA AADT<=6000:	Flat
6	7	8	9	10			Rolling
6	6	6	7	8			Mountainous
6	6	6	7	8		MA AADT>2000:	Flat
6	6	6	7	8			Rolling
4	4	4	6	8			Mountainous
4	5	6	7	8		MA AADT<=2000:	Flat
4	5	6	7	8			Rolling
4	4	4	6	6			Mountainous
2	3	4	6	8		Coll.'s AADT>1000:	Flat
2	3	4	6	8			Rolling
2	3	4	6	6			Mountainous
0	0	2	4	4		Coll.'s AADT=400-1000:	Flat
0	0	2	4	4			Rolling
0	0	2	4	4			Mountainous
0	0	0	2	2		Coll.'s AADT<400:	Flat
0	0	0	2	2			Rolling
0	0	0	2	2			Mountainous
					Urban:		
6	7	8	9			Interstate	
6	7	8	9			Other Freeway	
0	5	6	8			Other Principal Arterial	
0	5	6	8			Minor Arterial	
0	3	6	6			Collectors	

Table A-7. Default Shoulder Type Criteria[a]

UL	SDL	UST1	DL			
				Rural:		
2	2	2	2		Interstate:	Flat
2	2	2	2			Rolling
2	2	2	2			Mountainous
2	2	2	2		OPA AADT>6000:	Flat
2	2	2	2			Rolling
2	2	2	2			Mountainous
3	2	2	2		OPA AADT<=6000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT>2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	3	3	3		MA AADT<=2000:	Flat
3	3	3	3			Rolling
3	3	3	3			Mountainous
3	3	3	3		Coll.'s AADT>1000:	Flat
3	3	3	3			Rolling
3	3	3	3			Mountainous
4	3	3	3		Coll.'s AADT=400-1000:	Flat
4	3	3	3			Rolling
4	3	3	3			Mountainous
4	3	3	3		Coll.'s AADT<400:	Flat
4	3	3	3			Rolling
4	3	3	3			Mountainous
				Urban:		
1	1	1	1		Interstate	
1	1	1	1		Other Freeway	
4	2	2	2		Other Principal Arterial	
4	3	3	3		Minor Arterial	
4	3	3	3		Collectors	

a. Shoulder Type Codes: 1 = Surfaced; 2 - Stabilized; 3 = Earth; 4 = Curbed.

Table A-8. Default Horizontal Alignment Criteria[a]

UL	SDL	UST1	DL			
				Rural:		
2	2	2	1		Interstate:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
2	2	2	1		OPA AADT>6000:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
3	2	2	2		OPA AADT<=6000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT>2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT<=2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		Coll.'s AADT>1000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
4	3	3	2		Coll.'s AADT=400-1000:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous
4	3	3	2		Coll.'s AADT<400:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous
				Urban:		
2	2	2	1		Interstate	
2	2	2	1		Other Freeway	
3	2	2	1		Other Principal Arterial	

a. Alignment Codes: 1 = All curves meet design standards; 2 = Some curves below design standards; 3 = Curves with reduced speed; 4 = Several curves unsafe.

Table A-9. Default Vertical Alignment Criteria[a]

UL	SDL	UST1	DL			
				Rural:		
2	2	2	1		Interstate:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
2	2	2	1		OPA AADT>6000:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
3	2	2	2		OPA AADT<=6000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT>2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT<=2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		Coll.'s AADT>1000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
4	3	3	2		Coll.'s AADT=400-1000:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous
4	3	3	2		Coll.'s AADT<400:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous

a. Alignment Codes: 1 = All grades meet design standards; 2 = Some grades below design standards; 3 = Grades with reduced speed; 4 = Significant reduction of speed on grades.

Table A-10. Default Design Standards For Median Width (Feet)

DS			
	Rural:		
64		Interstate:	Flat
64			Rolling
16			Mountainous
40		OPA AADT>6000:	Flat
40			Rolling
16			Mountainous
40		OPA AADT<=6000:	Flat
40			Rolling
16			Mountainous
40		MA AADT>2000:	Flat
40			Rolling
16			Mountainous
0		MA AADT<=2000:	Flat
0			Rolling
0			Mountainous
0		Coll.'s AADT>1000:	Flat
0			Rolling
0			Mountainous
0		Coll.'s AADT=400-1000:	Flat
0			Rolling
0			Mountainous
0		Coll.'s AADT<400:	Flat
0			Rolling
0			Mountainous
	Urban:		
20		Freeway/Expressway by design	

Table A-11. Default Design Standards For Curves and Grades

Curve Class	Grade Class			
		Rural:		
1	3		Interstate:	Flat
1	3			Rolling
3	5			Mountainous
1	3		Other Principal Arterial:	Flat
1	3			Rolling
3	5			Mountainous
1	3		Minor Arterial:	Flat
2	3			Rolling
3	5			Mountainous
2	4		Major Collectors:	Flat
3	5			Rolling
4	6			Mountainous
		Urban:		
3			Interstate	
3			Other Freeway	
3			Other Principal Arterial	

Table A-12. Default Design Standards for Urban Sections

Surface Type[a]	Lane Width (Feet)	Shoulder Width (Feet)	
2	12	10	Freeway by design
2	12	10	Other divided
2	12	9	Undivided arterials
3	12	8	Undivided collectors

a. Surface Type Codes: 1 = High flexible; 2 = High rigid; 3 = Intermediate; 4 = Low; 5 = Unpaved.

Appendix B:

Induced Traffic and Induced Demand

"Induced" is a term implying that a particular condition is indirectly caused by another condition. In the case of traffic volumes, the term arose from the phenomenon that improvements to a highway—especially capacity improvements—seemed to result in more traffic choosing to use the road than would be the case if the highway were not improved. To an economist, this is an example of demand elasticity. Simply recognizing that travel demand is elastic, however, is not sufficient to reconcile the conflicting views of engineers, planners, and environmentalists. On one side are those who argue that transportation facilities are provided to serve land uses and support economic activity; on the other are those who claim that whatever capacity is provided soon fills up to the same level of congestion, gaining nothing. The truth can be better understood by defining induced demand in a way that uses the concept of elasticity.

This appendix describes the concepts guiding several modifications that were made to the HERS model for the 1997 *Conditions and Performance* report to Congress. With minor exceptions noted below, the model implements the concepts as they are described here.[1]

B.1 Concepts of Induced Demand

Frequent references are made in transportation planning to the concept of induced demand, but the term remains ambiguous. The intent here is to define the relevant concepts, and show how they can represent demand for purposes of benefit-cost evaluation of capital improvement projects.

B.1.1 Exogenous Demand Factors

Historically, demand forecasts in urban transportation planning have been based on exogenous variables such as land use, population, employment, and income. Once these variables are measured or estimated, the result is a "point" estimate for traffic volume at a future date. Demand, in this sense, is influenced by neither transportation infrastructure nor money price, but is determined entirely by exogenous factors.

If demand is determined by forces beyond the control of the transportation planner, then failure amounts to not having adequate facilities to handle it, and the planner is simply a messenger. Alternatively, if the facility creates its own demand, the planner is just furthering the careers of planners.

1. This Appendix was written by Douglass B. Lee, Jr., Lisa A. Klein, and Gregorio Camus, and was published in the *Transportation Research Record* No. 1659 (1999). The authors thank E. Ross Crichton, William Goldsmith, and Anthony Rufolo for valuable comments and suggestions.

B.1.2 Demand Fills Capacity

A contrasting concept has emerged, claiming that additional capacity stimulates corresponding increases in demand. This concept embodies the "build it and they will come" idea—or a belief in the existence of "latent demand," which suggests that there are willing buyers who will express their demand for travel once the service is offered.[2] In growing urban areas, the evidence from recent decades seemed to support this interpretation.

Although the idea has not been implemented as a formal forecasting method, the implication is that demand is entirely *end*ogenous. If true, the policy choice is whether to permit travel to grow or to suppress it.

B.1.3 Elastic Demand

Perhaps the first recognition that demand responded to endogenous factors was the assertion that congestion is self-regulating, implying an automatic balancing of supply and demand. More recently, the economist's concept of demand being a relationship between price and quantity demanded has become accepted, if not necessarily applied in practice. From this perspective, all endogenous changes in volume are movements along the demand curve, whether they are called latent, induced, or something else. If "price" is generalized to include travel time, operating costs, and accidents, then changes in capacity and alignment alter the "price" and thereby cause movements along the demand curve.

Overall, then, travel demand is the result of a combination of both exogenous factors that determine the location of the demand curve, and endogenous factors that determine the price-volume point along the demand curve.

B.2 Short Run versus Long Run

The short run can be any period of time over which something remains fixed. What is fixed might be the capacity of a highway, fuel efficiency of the vehicle fleet, locations of employment, or anything else that changes slowly. The long run is enough time for these characteristics to change. In transportation planning, the short run typically is assumed to be about 1 year, but the dividing line depends upon the practical context.

B.2.1 Short-Run Elasticity

Demand elasticity is the responsiveness of quantity demanded to changes in price. Price is generalized for travel demand to include travel time, operating costs, and accidents, as well as user charges.[3] Everything included in this generalized price is an endogenous factor with respect to induced traffic. An increase in capacity that lowers travel time, for example, results in additional travel if the elasticity is not zero.

2. For an interpretation of latent demand, see Small (1992), pp. 112-116, or Small, Winston, and Evans (1989)
3. The generalized price embodied in HERS includes time, operating costs, and accidents, but no user charges *per se*. The implications of this omission are discussed in greater depth in Appendix D.

Short-run demand elasticity tends to be lower (i.e., less elastic) than long-run elasticity, because more opportunities to increase or reduce consumption can be developed over the long run than in the short run, while short-run options do not diminish in the long run. If the price of fuel goes up, for example, highway travelers can reduce fuel consumption by taking fewer trips and chaining trips together, by carpooling to share expenses, by driving in ways that achieve better mileage, and by taking a larger share of trips on transit. In the long run they also can switch to more fuel-efficient vehicles, and change their workplace and residence locations. If the price stays high, vehicle manufacturers will develop and produce more fuel-efficient vehicles, and better transit service may be offered.

B.2.2 Long-Run Elasticity

Though the distinction between short-run and long-run demand is really a continuum rather than two discrete states, the separation is useful both conceptually and for modeling purposes. In Figure B-1, two short run demand curves are shown in relation to their common long run demand curve (the latter indicated by a dashed line). Demand could be for a facility, a corridor, or even travel in a region. At a “long run” price of p_1 the volume is v_1 and the short run demand curve D_1 applies, such that changes in the price cause changes in volume along this demand curve in the short run. If the price drops to p_2, for example, then volume will increase to a flow of $v_{1,s}$. If the price stays at that level for the long run, then the short run demand curve will shift outward to D_2, resulting in the volume v_2 at that price. If the price were then to go back up to p_1, volume would only drop to $v_{2,s}$ in the short run, but eventually back to v_1 in the long run.

For example, secular declines in real fuel prices have led to increases in the size and weight of vehicles and concomitant declines in their fuel economy; if the price of fuel were to increase, gasoline consumption would drop but the vehicle fleet would take time to evolve to a more fuel-efficient average. Changes are not necessarily completely reversible—knowledge gained from research leading to advances in technology in, for example, fuel efficiency, is not lost when the need is lessened, but its application tends to diminish.

B.2.3 Induced Traffic versus Induced Demand

A similar distinction can be made between induced *traffic* (or induced travel) and induced *demand*, by applying the short-run and long-run concepts. It is assumed that demand is fixed in the short run, so changes in volumes are the result of movements along the demand curve; but in the long run, the short-run demand curve can shift. In this way, these terms are defined so that induced traffic is a movement along the *short-run* demand curve, while induced demand is a movement along the *long-run* demand curve, or an endogenous *shift* in the short-run demand curve.

In Figure B-1, no time direction is implied on the horizontal dimension; the shape of the long-run demand curve does not mean that price declines over time. Nor are the short-run demand curves necessarily ordered from one to two; demand could start at D_2 and then shift to D_1. The diagram shows only the relationship between price and volume under short-run and long-run conditions.

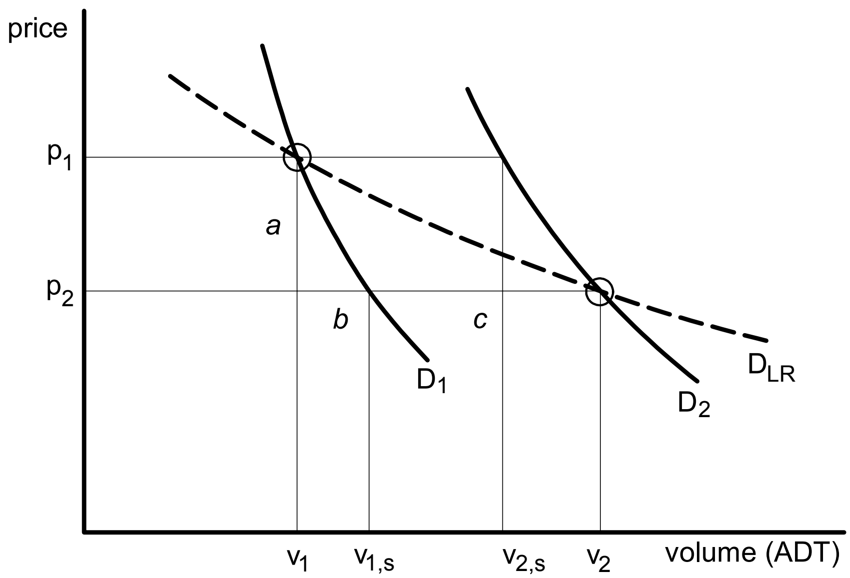

Figure B-1. Long Run Demand With Short Run Demand Curves.

B.2.4 Disaggregation of Long Run Elasticity

Long-run elasticity—as with any other demand elasticity—is a ratio of the percentage of change in quantity demanded to the percentage of change in the price of the good. Referring to Figure B-1, the first circled point at (p_1,v_1) is taken to represent a point on both the short-run and long-run demand curves. The second circled point at (p_2,v_2) represents the long-run result of a price change, which lies on the previous long-run demand curve but also on a new short-run curve. The arc elasticity between the two points is

$$e_{LR} = \frac{\%\Delta v}{\%\Delta p} = \frac{\Delta v}{\Delta p} \times \frac{p_1}{v_1} = \left(\frac{v_2 \angle v_1}{p_2 \angle p_1}\right) \times \frac{p_1}{v_1} \qquad \textit{Eq. B.1}$$

where e_{LR} is the long run elasticity of demand. If the following simplifications are made for ease of presentation,

$$\begin{aligned} a &= p_2 \angle p_1 \\ b &= v_{1,s} \angle v_1 \\ c &= v_2 \angle v_{1,s} \end{aligned} \qquad \textit{Eq. B.2}$$

as shown in Figure B-1, then the long run elasticity can be represented as

$$e_{LR} = \frac{b+c}{a} \times \frac{p_1}{v_1} = \left(\frac{b}{a} \times \frac{p_1}{v_1}\right) + \left(\frac{c}{a} \times \frac{p_1}{v_1}\right) \qquad \textit{Eq. B.3}$$

where the first term in parentheses is the short run elasticity (e_{SR}) and the second term is the shift in the demand curve over the long run, represented as an elasticity. Thus the long run elasticity is the sum of the e_{SR} and a purely long run component which will be called the long run share, e_{LRS}, defined as

$$e_{LRS} = \left(\frac{c}{a} \times \frac{p_1}{v_1}\right) = \left(\frac{v_2 \angle v_{1,s}}{p_2 \angle p_1}\right) \times \frac{p_1}{v_1} \qquad \textbf{\textit{Eq. B.4}}$$

so

$$e_{LR} = e_{SR} + e_{LRS} \qquad \textbf{\textit{Eq. B.5}}$$

The e_{LRS} component can be interpreted in the same way as a normal elasticity, and can be empirically measured as the difference between the short run elasticity and the long run elasticity estimated for the appropriate time period.[4]

B.3 Induced Traffic

As defined above, induced *traffic* is a movement along the short-run demand curve. Common usage of the term “induced” suggests additional traffic—that is, an increase in volume. Decreases might be called disinduced, deterred, or discouraged traffic. For present purposes, the term refers to any endogenous change, whether positive or negative. Increased congestion or higher tolls, other things being equal, will cause a reduction in volumes. If this occurs in the short run, this is negative induced traffic.

Some of the possible sources of induced traffic include the following:

- Diverted traffic that changes its route to the improved facility;
- Rescheduled traffic that previously used the facility at a different time, spreading or contracting the peak;
- Shifts from other modes, which might or might not have used the facility before, and which include changes in occupancy;
- Destination shifts, resulting from facility improvement; and
- Additional travel by persons already using, or in the market for, the facility.

Demand forecasts for a new or improved facility always include at least some of these sources, although such estimates seldom explicitly recognize a generalized price as the explanatory variable and do not produce a schedule of price-volume combinations.

B.3.1 Partial and General Equilibrium Demand Curves

All demand curves portrayed in this analysis are assumed to be general equilibrium demand curves, even those for the short run. They include traffic shifted to or from other modes or from alternative facilities. A partial equilibrium demand curve, as represented in Figure B-2, includes only the travel for those already in the market,

4. See Taplin (1982) for theory.

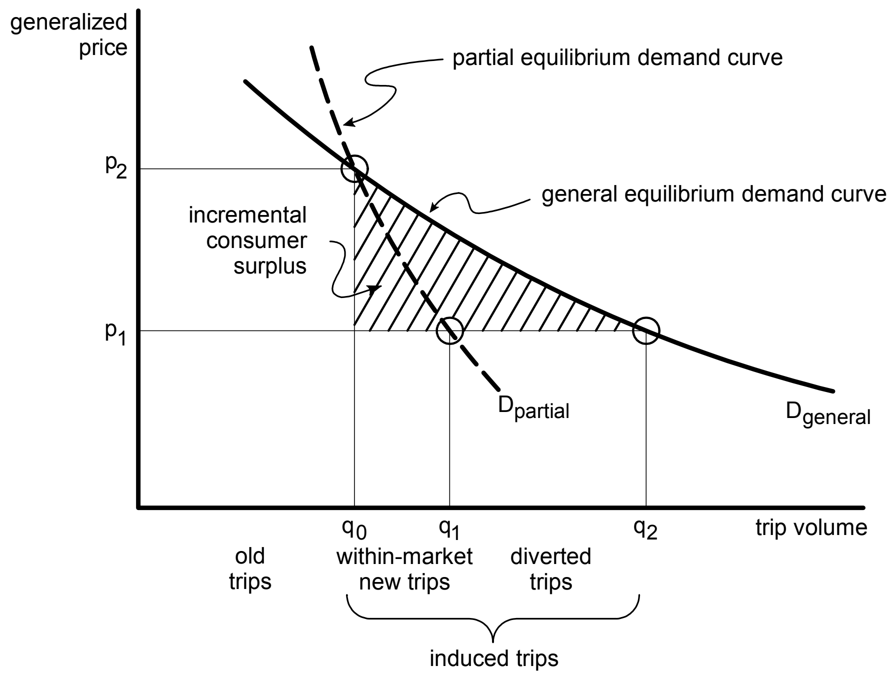

Figure B-2. Partial and General Equilibrium Demand Curves.

whether they are currently taking trips or not (e.g., a person who did not travel at all in this corridor but who chose to do so after the price was reduced, and not by shifting a trip from another time or place). If the demand curve includes diverted travelers (from other modes, routes, times, or destinations), then it will be more elastic than the corresponding partial demand curve because more options are offered. Thus some of the (short run) induced travel comes from new trips by persons already in the market, and some comes from trips diverted from other markets.

For every point on the general equilibrium demand curve there is a corresponding partial demand curve, representing the hypothetical demand that would occur if there were no substitution between markets. If the price were raised, for example, from a point on the general equilibrium demand curve, a movement up the partial demand curve would imply that the travelers could not divert to another time or facility. Not surprisingly, such a demand curve cannot be observed in practice.

Because demand forecasts usually include diverted trips, practical demand forecasts are aimed implicitly at constructing (or locating points on) a general equilibrium demand curve. If the demand is for a single facility, then induced traffic will appear large relative to previous volumes, because most of the change in trips will be from diverted trips. At the regional level, induced traffic—if it were actually estimated—would be a smaller share of total traffic growth, because only trips diverted from other regions, plus substitutions between transportation and other goods, make up the induced share. For project evaluation, diverted travel and other components of induced demand, as measured in consumer surplus, represent the net valuation of systemwide impacts.[5]

B.3.2 "Gross" versus "Net" Induced Traffic

In Figure B-2, all of the movement along the general equilibrium demand curve stimulated by the reduction in price from p_0 to p_1 is labeled "induced trips." A portion of this induced traffic is labeled "diverted trips." If the diverted trips are removed from the total "gross" induced traffic, the residual might be called "net" induced traffic. Some analysts prefer that the term induced be restricted to mean *net* induced trips, and the others be left as diverted trips.[6]

For some purposes, this usage has an appeal, but the distinction is a difficult one to make. A trip between the same origin and destination but using a different route is clearly a diverted trip, but trips at other times, or to other destinations are less obvious. If the improved facility prompts a person to go to a movie instead of renting a video, and the video store is much closer, is this induced or diverted? Suppose the person would have walked to the video store. Or suppose the person would have had the video delivered, and the van would have used the same facility before it was improved. What can be observed directly is that more vehicles use the facility after it is improved, and that trips in the region do not go up by as large an amount as the volume on the improved facility. Labeling which particular travel is "new" and which is "diverted," however, is difficult and probably not necessary.

B.3.3 Schedule Delay and Peak Shifting

As noted earlier, changes in the generalized price may lead to changes in schedule. Peak congestion can be at least partially avoided by leaving earlier or later than preferred. A reduction in peak travel time will cause some travelers to join the peak because the cost to them of schedule delay (departing at a different time than preferred) is less then the new peak delay.[7] Induced traffic, therefore, can be diverted from other times as well as other routes.

If the demand curve represents both peak and off-peak, then the elasticity will be lower than if peak is separated from off-peak. Because the two periods are so closely interrelated (off-peak demand depends upon peak price, and vice versa), separating them for benefit-cost purposes can be tricky, but this is one way to include benefits from reducing schedule delay.

B.4 Induced Demand

For purposes of evaluating costs and benefits, the overall analysis period for a project (generally the project lifetime, e.g., twenty years) is broken into a series of discrete time periods, during each of which the demand curve is assumed to be fixed. A baseline long range forecast is used to establish the short run demand curve for each period.

5. See Dargay and Goodwin (1995), Mackie (1996), and Williams and Yamashita (1992).
6. Examples include Dowling (1994), Heanue (1997). Holder and Stover (1972) and SACTRA (1994).
7. See Small (1992).

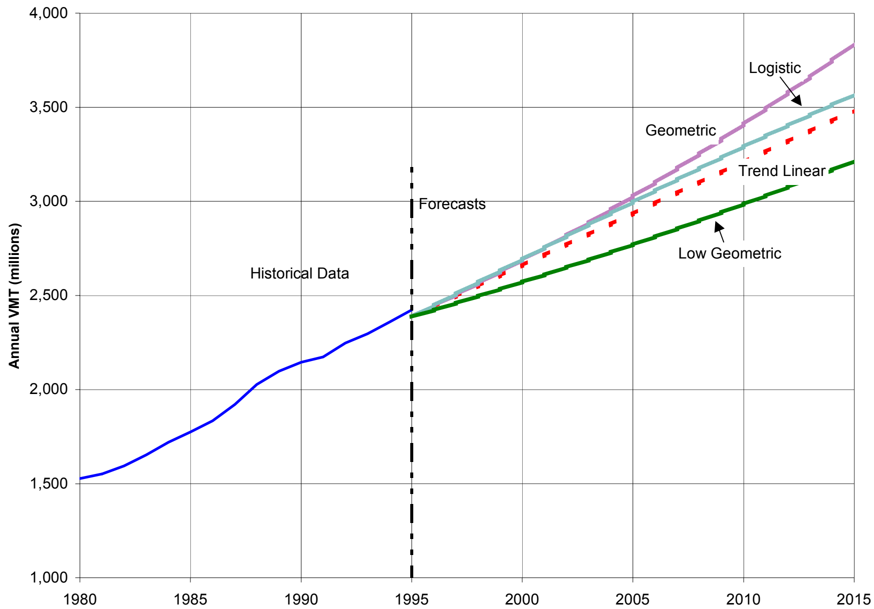

Figure B-3. Alternative Long Run Travel Forecasts

B.4.1 Baseline Demand Forecast

A demand forecast is a functional relationship between time and traffic volume, assuming a set of conditions. *Exogenous* conditions include population growth, economic growth, land use patterns, and available substitute transportation alternatives. *Endogenous* conditions include capacity, level of service (LOS), and user fees. For the present analysis, all endogenous factors are represented in the generalized price. Both capacity and LOS, for example, would both be subsumed under travel time cost and included in the generalized price.

The baseline long-run demand forecast assumes a generalized price, as well as whatever exogenous factors are thought to be relevant by the forecaster. Alternative forecasts might be constructed under different assumptions, as shown in Figure B-3. One such forecast is selected for constructing the short run demand curves.

B.4.2 Breaking the Forecast Into Discrete Periods

The distinction between long-run induced demand and short-run induced travel is implemented by constructing a short-run demand curve for each of the shorter demand periods (e.g. 1-5 years), and allowing the initial curve to shift, depending upon previous improvements. The forecast becomes a series of discrete points—shown circled in Figure B-4—that provide the calibration points for the associated short-run demand curves. The short-run demand curve can be a straight line calibrated with an elasticity, a constant elasticity demand curve, or some other functional form that can be fitted to a single price-quantity combination. The elasticity chosen should be appropriate to the length of the demand period.[8]

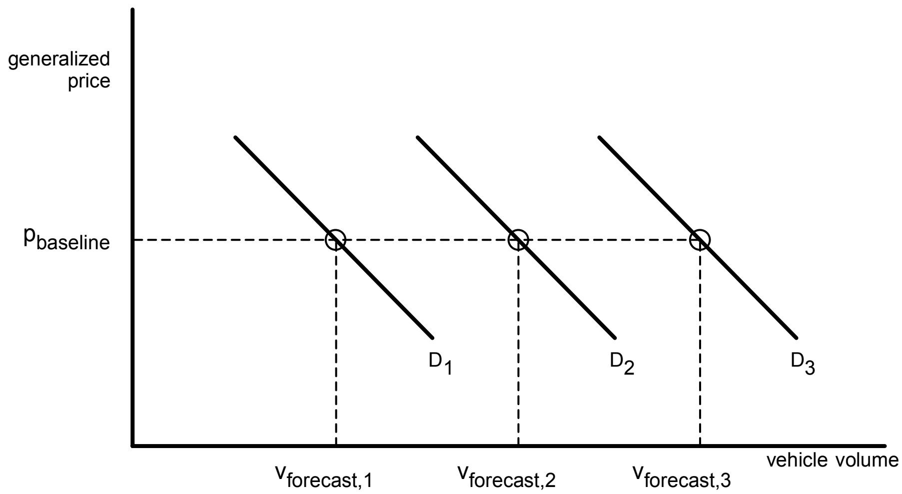

Figure B-4. Baseline demand forecast for several periods

A single, fitted short-run demand curve is shown in Figure B-5, along with other relevant prices and volumes. The price from the previous period $p_{final,\ t-1}$ is adjusted to account for traffic growth, pavement wear, accident rates, and user fee changes that have occurred since the previous period. The result is $p_{no\ improvement}$. Alternative improvements for the current period are evaluated, and, if any are feasible, the best is implemented. This leads to the $p_{improved}$ price, which becomes the initial price for the next demand period. If no improvement is selected, the unimproved price carries into the next period.

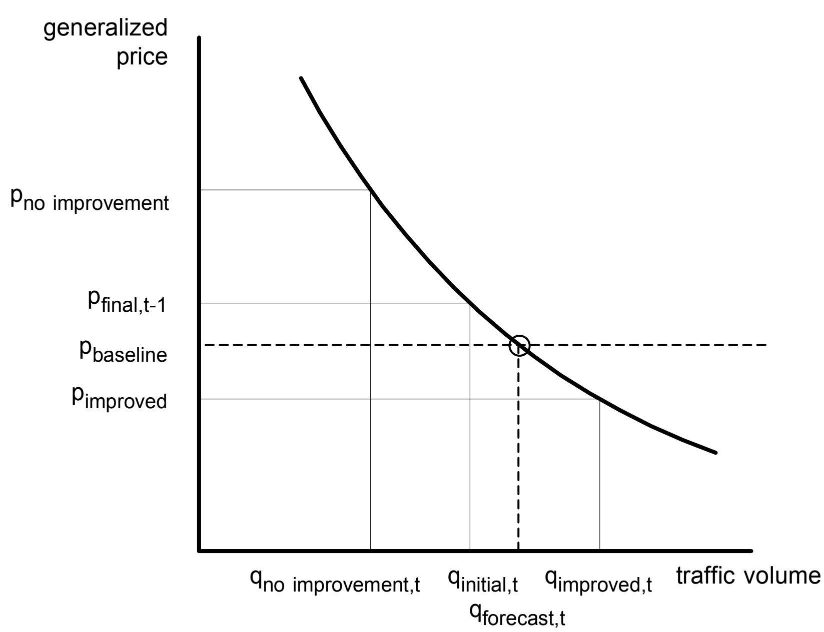

Figure B-5. Short Run Demand Showing Prices With and Without Improvements.

8. Currently, the demand period or "funding period" in HERS is five years, so the short run elasticity should be selected to allow for adjustments that can be expected to take place within that span of time.

B.4.3 Long Run Shifts in the Demand Curve

Evolution of demand in the long run is built upon what takes place in the short run. Operationally, induced *demand* is defined to be the shift in the short run demand curve caused by the price in the previous period. If the price in all previous periods is the same as the baseline price, then the demand curve is fitted to the baseline forecast for that period. If an improvement is made in one period that reduces the price below the baseline price, this leads to a shifting of the demand curve outward, according to the percent by which the price in the previous period is below the baseline price. If no improvement is made, the price increases relative to the baseline forecast price, and the demand curve shifts inward in the next period. These two possibilities are shown in Figure B-6. For example, a price of $p_{no\ improvement}$ will shift the subsequent demand curve inward from $q_{forecast}$ by a percentage equal to $(p_{baseline} \angle p_{no\ improvement}) \times e_{LRS}$.

The relationship between the difference in price of the final, improved—or not improved—price and the baseline price, for one period, and the horizontal shift in the demand curve in the next period, is governed by the long-run share e_{LRS}, as described above.[9] There is no long run demand curve as such, but the shift attributed to induced demand is a displacement of the short run demand calibration point along the baseline price line.

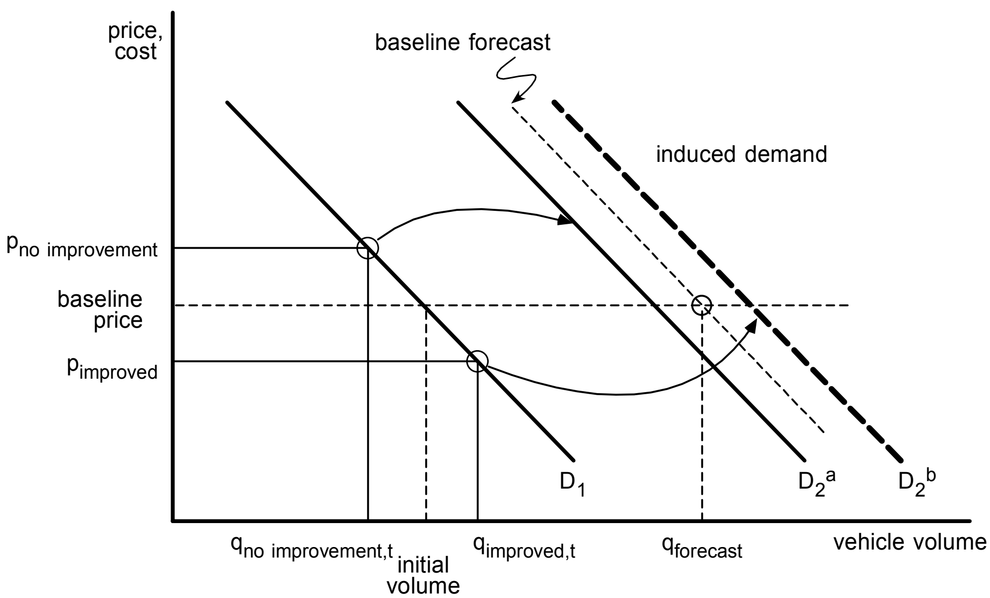

Figure B-6. Long Run Induced Demand Shift From One Period to the Next.

Incorporating induced demand, then, allows each period's demand curve to be a function of the previous period's investment, since it affects price to the user. Investment that keeps the price in each period below the baseline price for the baseline forecast produces demand curves that shift farther and farther outward, compared with the baseline forecast. Similarly, if improvements are not made and price is allowed to rise

9. Figure B.2.4 “Disaggregation of Long Run Elasticity” on page B-4

in each period (e.g., due to congestion, pavement roughness, and accidents), the demand curve will be shifted continually inward relative to the baseline.

The magnitude of this shift—the sensitivity of long-run demand to investment and pricing—is determined by the e_{LRS} parameter. The shorter the time period for the short run, the lower should be the long-run elasticity shift from period to period. If the long-run induced demand parameter is zero, the location of each short-run demand curve would be determined by the baseline forecast, without regard for which—if any—improvements were made in any demand period. Short-run movements along the demand curve still could occur, depending on the short-run price elasticity, but there would be no cumulative endogenous effects from one period to the next. Alternatively, with a high e_{LRS}, induced demand could alter the baseline forecast, even to the point of potentially offsetting the trend of the initial forecast, such leading to growth in demand (from keeping the price low) despite a declining forecast, or causing a decline in demand despite a growth forecast (traffic is deterred by congestion and bad pavement, a consequence of no improvements).

B.4.4 Getting to the Long Run

Empirical estimates of the two elasticities depend upon the length of the short-run time period and the rate of adjustment to changes in price. The length of time between a change in conditions and a new equilibrium is somewhat arbitrary, because other conditions change before equilibrium is reached; however, the process is one of accelerating initial response followed by gradual refinement. In the context of highway volume adjustments in response to changes in the generalized price of travel, the short run is up to a year. The long run—allowing for changes in residence and workplace locations—begins within a year but may not run its course for upwards of 20 years. Such changes are not likely to be motivated solely by changes in transportation prices, but may take transportation user costs into account when the change is made for other reasons (e.g., new job, change in income, change in family).

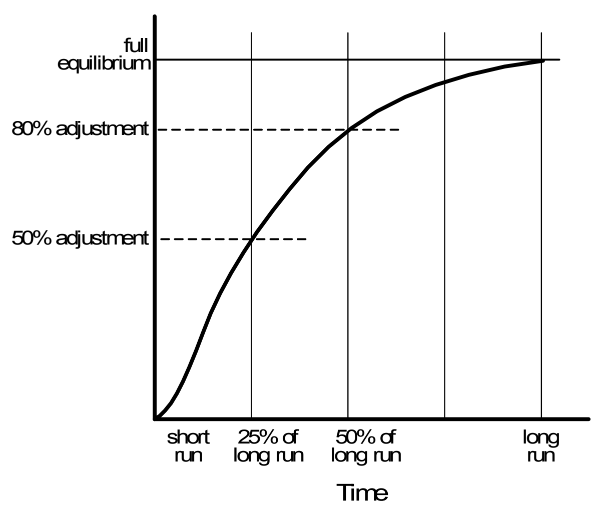

Figure B-7. Path to Long Run Equilibrium.

An approximate adjustment curve is shown in Figure B-7. Although the curve is not fitted to specific data, it reflects the generally observed pattern that roughly half the adjustments take place within about a quarter of the time to long run equilibrium.[10] If the full long-run adjustment period is 10 to 20 years, then half the long-run elasticity occurs within the first 2.5 to 5 years. There might be some accelerating adjustment in the first year, as shown, based on the idea that responses don't occur until consumers become sure the price change will stick, or until they begin feeling its effects.

B.4.5 Empirical Estimates of Short and Long Run Elasticities

Many studies have estimated travel-demand elasticities, but one of the difficulties in interpreting these results is the uncertainty of the time frame that is applicable to the data. Another confounding problem is the ambiguity of the base of the observed elasticity; because most of the empirical cases observe a change in a small component of the total price of travel, the base for computing the percentage change in price often is not obvious and might not be given explicit treatment. The potential differences are large (e.g., a factor of three or more).[11]

The parameter sought is the elasticity of vehicle travel with respect to its own price, including user fees, operating costs, and travel time. Studies undertaken to date suggest that short-run elasticities tend to fall in a -0.5 to -1.0 range, and long-run elasticities from -1.0 to -2.0; a within-period short-run elasticity for a 5-year period would thus be -0.6 to -1.0 and the between-period elasticity from -1.0 to -1.6, yielding an e_{LRS} of about -0.4 to -1.0.

B.4.6 Interpreting Demand Forecasts

Two aspects of the demand forecast are of particular interest. One is how to impute a presumed price to the baseline forecast. The second is whether long-run feedback of transportation investments on the demand curve has been incorporated into the forecast.

- Baseline Price. Although the generalized price behind a demand forecast is seldom made explicit, such attributes as LOS and accident rates may be, and others can be guessed. Pavement quality is probably assumed to be good, and operating costs are typical for the conditions (terrain, vehicle type, congestion). The current LOS can be assumed as a default.
- Long-Run Demand Feedback. Constructing or expanding a facility will induce some travel in the long run even if the price is unchanged from the baseline. Therefore, the baseline forecast should include growth in travel that will result from traffic-generating activities that locate to take advantage of the services provided by the facility at the baseline price. The long-run elasticity amplifies this effect up or down, but does not substitute for it.

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10. Cambridge Systematics, and JHK Associates (1979), Dowling Associates (1993), Dowling and Colman (1995), Goodwin (1998). Hansen (1995), Hansen, Gillen, Dobbins, Huang, and Puvathingal (1993), Kroes, Daly, Gunn, and Van der Hoorn (1996), and Pells (1993) study the time lag in response to highway capacity increases; Cairns, et al. (1998) study responses to reductions in capacity.
11. The empirical evidence and methods for estimating highway travel demand elasticities are covered in Appendix C.

If forecasts are based on historical patterns over a time horizon of half a dozen years or more, then the feedback effect implicitly is built in. Whether it needs to be made explicit or refined is an open question, but the impacts of errors in out-year forecasts are suppressed somewhat by discounting.

B.5 Summary

Some of the ambiguity and confusion that surrounds the discussion of induced demand might be dispelled by applying the following definitions and principles:

1. The term *induced* means a movement along a travel demand curve as a result of changes in *endogenous* factors, which can be represented as components (time, running cost, money) of a generalized price.
2. The measurement of induced travel is dependent upon the *market* for which the demand curve is defined; induced travel defined at the facility level will include traffic diverted from parallel routes, while induced travel at the regional level will include only trips that are new to the region.
3. A useful distinction can be made between short-run demand and long-run demand. Movement along the *short*-run demand curve amounts to *induced traffic*. However, movement along the long-run demand curve constitutes a *shift* in the short-run demand; this can be called *induced demand*.
4. Benefit-cost evaluation of projects requires that baseline demand forecasts be adjusted to take into account induced demand, both short and long run; simply stated, improvements that change user costs should be evaluated in the light of whatever changes in volume will actually occur. Such demand curves are referred to as general-equilibrium demand curves.
5. If the short-run elasticity is zero, then traffic volumes are unresponsive to changes in price within a single demand period, and the demand curve is vertical. If the elasticity of the long-run share (i.e., excluding short-run effects) is zero, then there are no long-run effects (e.g., no investment in highway-related facilities or land-use changes) stimulated by highway pricing and investment policies. Empirically, neither of these conditions seems to apply.

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Appendix C:

Demand Elasticities for Highway Travel

Douglass B. Lee, Jr. and Mark W. Burris[1]

An elasticity summarizes a large amount of information in a single number, including the choices of consumers with different preferences, with different options, which change over time. The elasticity concept normalizes for the measurement scales (e.g., pounds or kilograms, dollars or pesos) and price levels (to the degree that the demand curve is constant elasticity), but other factors are simply averaged over the consumers being observed. Moreover, although the price elasticity of travel demand is frequently mentioned in discussion as if it were a single datum, the many empirical estimates often measure conceptually different things.

The review and synthesis presented in this appendix was conducted for the purpose of establishing values for use in the HERS model to represent the short-run generalized-price elasticity of demand on a given highway section, and to estimate the long-run share parameter used in the model for estimating induced demand, as described in Appendix B, "Induced Traffic and Induced Demand." For the 2001 *Conditions and Performance* report to Congress, the values selected were -1.0 for short-run elasticity, and -0.6 for the long-run elasticity supplement, giving a full long-run elasticity of -1.6.

C.1 Theory

C.1.1 The Meaning of Elasticity

As an empirical measure, an elasticity is a microeconomic aggregate: it summarizes demand in a specific market at a point in time, at or near the prevailing price and quantity. A market could be a highway facility, a corridor, or an entire region. A point in time might be a peak hour, or a daily average. The basic concept can be represented as an arc elasticity between two demand points,

$$e = \frac{\%\Delta v}{\%\Delta p} = \frac{\Delta v}{\Delta p} \times \frac{p_0}{v_0} \qquad \textit{Eq. C.1}$$

where v_0 = initial traffic volume and p_0 = initial price. Elasticity can be thought of as a measure of slope normalized for the arbitrary measurement scales of p and v, and, indeed, the form to the right of the second equal sign is a slope multiplied by the ini-

1. The authors thank E. Ross Crichton, Mark Delucchi, William Goldsmith, and Phil Goodwin for comments on an earlier draft and many helpful suggestions.

tial demand point. If the derivative of the demand curve is substituted for the slope, the elasticity is instantaneous at the given point, rather than over an arc. For exposition, the arc form will be used, but the principles apply to either form.

C.1.1.1 Transferability

Because an elasticity is simply a summary of the behavior of a particular group of consumers for some period of time, there is no reason to believe that the same elasticity measure will have the same value at another time or place. At a different time point on the same facility, a different group of users may respond differently to a change in price, because they have different incomes, demographic characteristics, and different purposes. Additionally, prices in related markets (e.g., parallel facilities) may be different. If different facilities are being compared, all of the above may be different as well as differing substitute alternatives (routes, carpool and transit options, destinations, schedule options). Different days, seasons, regions, and forms of “price” all limit the transferability of an elasticity measured in one context to another context.

Hence—unlike the speed of light or the age of a rock—there is no underlying true number waiting to be discovered. Similar circumstances are likely to exhibit roughly similar elasticities, but the most important characteristics of these circumstances need to be made explicit.

C.1.1.2 Price, Output, and Market

The basic economic model of exchange reconciles supply and demand in a market, using price. The “price” is the market value of the resources given up by the buyer and received by the seller, accomplished in modern markets by means of some form of money that both parties agree to use as representing valuable resources. The market of interest in the present context is highway travel, measured as vehicle miles of travel (VMT). A single market has a single price, so a highway market could be a street length between intersections at a specific time of day. The concept of a market can be applied more broadly, however, to consist of a facility whose demand is averaged over the day, or a network of facilities. Elasticities will generally be larger (elastic) the more alternatives (route shift, time of day shift, add or forego trip) are available, and smaller (inelastic) the more broadly the market is defined (e.g., region versus facility). For present purposes, the focus is on a single facility, and its daily VMT.

C.1.1.3 Money Price

If the price measure were limited to the money price paid by the user to obtain the services of the highway, then such characteristics as travel time, pavement roughness, risk of accident, scenery, and curves and grades would be attributes of the service. Such a money price (assuming the user had access to a vehicle) would be a multi-part price consisting of vehicle registration fee, drivers’ license fee, excise taxes on fuel and tires, and tolls.

This formulation of the highway market has limited usefulness for several reasons. Primarily, the fees paid are a small part of the total cost to the user of highway travel, and attributes of the good (such as travel time) dominate the choice rather than price. Because travel is a derived demand, at least some of the attributes can be thought of as part of the cost to be minimized, including time and operating costs as well as user fees.

C.1.2 Generalized Price and Its Components

An alternative formulation is to treat some of the attributes as disutilities, and translate them into a dollar price. Operation of the vehicle, travel delay, and tolls are thus all costs to the user, or components of the price. In practice, the only way to estimate the demand elasticity of highway travel with respect to generalized price is to build up total travel demand elasticity from elasticities of the components of user costs.

If the price of a service is made up of several components, then the elasticity of demand may be broken into portions representing the components (or their elasticities). The relationship between the component elasticities and the overall elasticity can be viewed in several ways, the simplest being as arbitrary divisions of the price, the more complex way being as a set of input factors that must be purchased separately.

C.1.2.1 Sum of the Components of Price

Suppose the price for a particular good is $2.40 (1st component) plus $1.60 (2nd component); then the price of the good is simply $4.00. Assuming that the price elasticity for this good is a known (say -0.8), then a change in its price (say -$0.80) implies a specific increase in the quantity demanded (up 16%). This example is shown in the top row and righthand column of Table C-1.

Table C-1. Example price components

	1st component	2nd component	Overall
price	$ 2.40	$ 1.60	$ 4.00
change in price	$ (0.80)	$ -	$ (0.80)
% change in price	-33%	0	-20%
share of price	60%	40%	100%
elasticity	-0.48	-0.32	-0.80
% change in quantity	16%	0%	16%

From the standpoint of one component (say, the 1st), this price change is a different percentage (-33%) than from the standpoint of overall price (-20%). When the elasticity of demand with respect to the price component is measured (or observed), it is smaller (-33%/+16% = -0.48) than the overall elasticity because the relative price change is magnified whereas the quantity change is the same.

If the share of the component in the total price is also known, then the overall price elasticity can be calculated (-0.80 = -0.48/0.60) from the component elasticity (or the reverse, as is done in Table C-1). If the price change is applied to the other component, or spread between them, the component elasticities and price shares are unaffected, and the percent change in quantity will sum to the overall change.

Thus elasticities can be observed empirically for components and the overall elasticity inferred, or the overall elasticity can be "decomposed" into separate elasticities for each component. Price components are necessarily stated in common numeraire units ($), and the elasticity calculated for each component always implies the same overall price elasticity. Empirical estimates, of course, may contain noise or error and therefore not give consistent overall elasticity values.

C.1.2.2 A More General Case

The above example is trivial in its application, but provides a framework for incorporating more realistic complexity. In such a model, the separate price components can be viewed as inputs (vehicle, fuel, time, risk, highway space) that are purchased (car payments, excise taxes, tolls) and integrated by the producer (the highway user) to yield an output (vehicle miles of travel). This process sounds a bit like a supply function, but actually it is still a demand function: the user expresses her/his willingness to pay by buying the ingredients and spending the time. This perspective, however, raises some problems with respect to elasticities:

1. In order to combine the components into a generalized price elasticity, the components need to be stated in dollars. We can calculate a "time" elasticity (a service quality elasticity) by observing the change in travel resulting from a change in the time required. We could keep the time elasticity separate from the toll elasticity, and (assuming independence) we could estimate the change in travel demanded by applying the elasticities separately but cumulatively. To add the elasticities together, however, requires that we put a value on travel time. Many empirical studies do this by observing how much money travelers are willing to spend to save time.

2. The relationship between a change in the price of an input and the generalized price of travel is not always one-for-one. An increase in the price of fuel leads to actions that reduce the rate at which fuel is consumed per vehicle mile. An increase in a toll or user fee will result in higher vehicle occupancy, reducing the number of vehicle miles demanded by less than would be the case if occupancy were forced to stay the same. Thus some allowance should be made, depending upon the component, for "leakage" or "shrinkage."

3. If inputs can be substituted for each other, a relative change in the price of one component may lead to a shift in the input mix. An increase in travel time might lead to adding features to the vehicle that improve comfort or make the time partially usable for something else (cell phone, sound system, talking books). An increase in the cost or risk of accidents might lead to slower speeds or more circuitous routes, adding to travel time. Opportunities for trading off tolls for time seem to be increasing.

The first problem will be handled by converting everything to dollars, the second problem will be addressed by including a shrinkage factor estimated for the specific component, and the third will be ignored.

C.1.3 Three Relationships: Component Elasticity, Shrinkage, and Overall Elasticity

Thus three relationships are central to estimating total demand elasticities from component elasticities: the component's own-price elasticity, the correspondence of a change in the price of the component to a change in the price of travel, and the expansion from the component to the total elasticity.

C.1.3.1 Price Elasticity for a Component

If X is a component of the price of travel, and we observe its own price elasticity, then

$$e_X = \frac{\Delta q_X}{\Delta p_X} \times \frac{p_X}{q_X} \qquad \textbf{\textit{Eq. C.2}}$$

where e_X is the demand price elasticity of good X, Δq_X is the change in the quantity of X that is consumed (e.g., gallons of fuel), Δp_X is the change in the price of the good (e.g., the price of gasoline at the pump), p_X is the initial price of the good, q_X is the initial quantity of the good, and $\Delta q_X/q_X$ is the percent change in the quantity of good X. This is a relationship between the price of the component and *its* consumption, not the consumption of the overall good of which X is a component.

C.1.3.2 Shrinkage of the Component

The latter relationship—between the price of X and the quantity demanded of another good—is a cross-elasticity. Higher fuel prices, for example, are partly absorbed in improved fuel mileage, so that the percentage reduction in fuel consumed is greater than the percentage reduction in VMT. The cross-elasticity of total travel with respect to the price of a component is

$$e_{T,X} = \frac{\%\Delta q_T}{\%\Delta p_X} = \frac{\%\Delta q_X}{\%\Delta p_X} \times \frac{\%\Delta q_T}{\%\Delta q_X} \qquad \textbf{\textit{Eq. C.3}}$$

where $e_{T,X}$ = elasticity of travel demand with respect to a change in the price of *X*. The term between the equal signs is simply the definition of a cross-elasticity, and the right-hand side indicates that the new elasticity can be obtained from the component elasticity using a factor for the percent by which travel changes for a given percent change in consumption of the component. Stated more simply, then,

$$e_{T,X} = \sigma \times e_X, \quad \sigma \le 1 \qquad \textbf{\textit{Eq. C.4}}$$

where σ = a shrinkage factor representing the share of a reduction (or change) in consumption of *X* that consists of reduction in travel. The extent of this "shrinkage" between the component price elasticity and travel demand elasticity depends upon the component, and the possibilities for economizing on the component other than by reducing travel. If σ = 1 then the component and travel are necessarily consumed in fixed proportions.

C.1.3.3 Expansion From Component to Total Elasticity

If the elasticity of VMT with respect to a part of the price is known, then the elasticity of total travel demand is simply an expansion from the part to the whole,

$$e_T = \frac{e_{T,X}}{p_X/p_T} = \frac{\sigma e_X}{p_X/p_T} \qquad \textbf{\textit{Eq. C.5}}$$

where e_T = implied demand elasticity for travel (the overall good), p_T is the price of travel, and the component elasticity e_X is substituted using Equation C.4. The bottom of the right-hand side is the share of the component in the total price of travel. For example, if the elasticity of fuel consumption with respect to its own price is -0.25, and the shrinkage factor is 0.6 (from increases in fuel efficiency), then the elasticity of *travel* with respect to fuel price is -0.15. If fuel is only 20 percent of the cost of travel, yet has an elasticity with respect to total travel of -0.15, then the implied generalized-price demand elasticity is -0.75 with respect to the total price of travel.

C.2 Empirical Estimation of Price Components

Considerable empirical evidence can be found in the literature, and this information can be re-interpreted with respect to generalized price elasticity.

C.2.1 From Evidence to Application

Although empirical studies are mainly oriented toward changes in one component of price, these studies can be extrapolated to the full generalized price. Once a total price elasticity is determined, then that value can be adjusted to apply to a specific context such as a highway section. This process is represented in Figure C-1. For use in the 2001 *Conditions and Performance* report, the section-level effects are assumed to cancel each other, on average, and the overall price elasticity is used for sections. The evidence and analysis presented here pertain primarily to passenger travel, although freight movement can be expected to respond in similar ways.

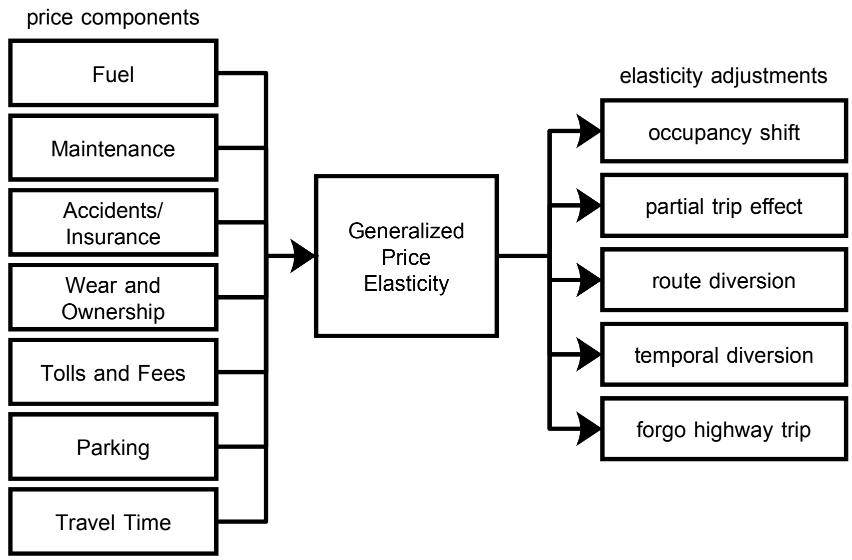

Figure C-1. Primary analytical steps in generating project-specific elasticities.

It is important to remember that the analysis concerns vehicle-trips, not person-trips. Although persons make the decisions for vehicles, vehicle trips are more readily observed, and the price typically applies to vehicle travel rather than to person trips.

C.2.2 Construction of Travel Demand Elasticities from User Cost Components

The methodological strategy for moving from information about the components of user cost or "price" to generalized travel demand elasticity is represented in Figure C-2 and described below:

1. The first step is an accounting problem to define the user cost categories for which data have been collected and tabulated, matched with those for which elasticities have been or could be measured. The units are in dollars per vehicle mile of travel.
2. Because price per VMT—even by component—is an average of unlike conditions (large and small cars, urban and rural traffic), a more robust result is obtained by considering several different data sources and reconciling the numbers. Again, the choice of measure must match whatever is used or implied in empirical elasticity estimates.
3. A major source of uncertainty in expanding from component to total price is which components should be included in the "price" to the user. Possibilities range from using only short- run variable out-of-pocket costs that the user "perceives," to all costs paid by the user including travel time.
4. Within this range of uncertainty, low and high percentage shares can be calculated for each of the price components.
5. Empirical estimates of any relevant elasticity estimates can be combed from the literature, formal or informal. Not all components are suitable for estimating elasticities empirically (e.g., accidents), and some that are suitable may not have been the subject of published estimates.

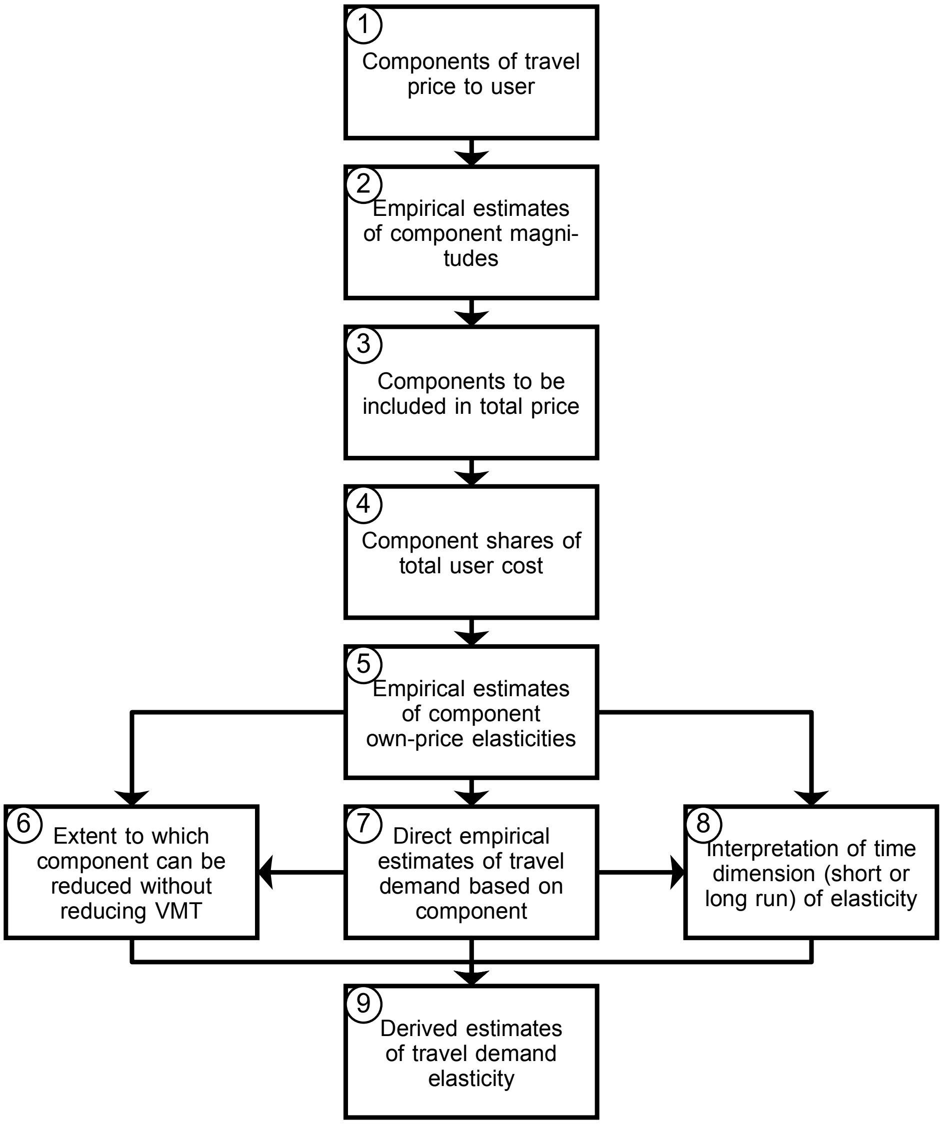

Figure C-2. Method for building generalized travel demand elasticities.

6. Given an own-price elasticity estimate for a component, and its share in the total price, the next problem to be resolved is the extent to which a change in the consumption of the component results in the same percentage change in VMT, i.e., the shrinkage factor.
7. For those instances in which a travel demand elasticity has been estimated from changes in the price of the component, the component elasticity can be inflated directly to the total demand elasticity; this information can also be compared to any own-price elasticities to assess the "leakage" into non-VMT changes.
8. All of the empirical elasticity estimates must be interpreted along several dimensions, the most important being whether it is a short-run or long-run estimate. Many published estimates are ambiguous regarding the time span covered.

9. The above information, subject to its range of uncertainty, can be distilled into estimates of short-run and long-run travel demand elasticities based on generalized price.

These steps are explained and implemented in more detail below.

C.2.3 Define User Cost Components

Seven categories of user cost are listed in Table C-2. They are intended to be non-overlapping and exhaustive. Fortunately, this set of categories is generally consistent with various estimates of user costs. The purpose of these categories is to be able to combine them in subsets that provide alternative measures of the "price," to distinguish fixed from variable costs as a means for defining the relevant costs, to match with empirical estimates of costs, and to match up with empirical elasticity estimates.

Table C-2. User Cost Accounting Framework

Category	Scope
Fuel	gasoline, diesel fuel, or other fuel consumed by motor vehicles, including taxes
Maintenance	oil, parts, periodic maintenance, unscheduled maintenance, tires, excise taxes
Accidents and Insurance	costs of accidents (internal), insurance administration and profit
Vehicle Wear and Ownership	wear and tear, additional depreciation, financing, sales and excise taxes
Tolls and Fees	tolls, registration fees, license fees
Parking	cost of parking to the user at work, shopping or other
Travel Time	dollar value of time spent in traveling

C.2.4 Estimates of Component Shares

Estimates of national averages for the cost components of highway travel are provided in Table C-3. All are intended to cover internal costs borne by users, omitting externalities, since elasticities necessarily must be based on internal costs. Four sources are presented, each of which offers a different orientation:

1. Back-of-Envelope: The value for the particular component is estimated from a few aggregate totals, rates, and averages. This approach provides a reality check on whether other results are plausible.
2. Delucchi:[2] In his research, Delucchi has made original estimates of national totals for most of the components for 1991, broken down finely enough to permit aggregation along several dimensions. For each item, he provides a low and high estimate, which are averaged here. His estimates are unique for including many imputed values, such as travel time, uncompensated accident costs borne directly by users, and accident costs paid from sources other than insurance.
3. Runzheimer:[3] The Runzheimer International Corporation is a consulting firm that collects data on highway vehicle costs and other business expenses,

2. Delucchi (1997).

Table C-3. Estimates of Components of User Cost ($/VMT)

Component	Back-of-Envelope	Delucchi	Runzheimer	FHWA
(1) Fuel	0.058	0.069	0.067	0.061
(2) Maintenance	0.087	0.073	0.052	0.053
(3) Accidents and Insurance	0.087	0.133	0.070	0.070
(4) Wear and Ownership	0.125	0.142	0.248	0.127
(5) Tolls, Fees	0.002	0.015	0.003	0.009
(6) Parking	0.022	0.004	0.019	0.013
(7) Time	0.306	0.344	0.344	0.344
Total Variable	0.232	0.275	0.189	0.184
Total Monetized	0.381	0.436	0.459	0.333
Total Variable w/ Time	0.538	0.620	0.495	0.490
Total Internal	0.687	0.780	0.765	0.639

Notes:

(1) Fuel -- BoE assumes $1.15 for fuel (including excise taxes) and 19.7 miles per gallon average fuel economy for all passenger vehicles (FHWA 1996 Highway Statistics); Delucchi value is sum of fuel costs, oil company producer surplus, and fuel taxes (Delucchi, 1998), divided by total 1991 US annual VMT of 2,172 billion (Highway Statistics); Runzheimer values are extracted by applying their 1998 percentage distribution of costs for and intermediate car to their estimates of annual fixed ($6,934) plus operating costs ($2,240) of a Ford Taurus (Runzheimer, 1997, 1998); FHWA values are for an intermediate sedan, including fuel taxes, at $1.196 per gallon (Jack Faucett Associates, 1991).

(2) Maintenance -- BoE based on assumed value of $1,000 per year for oil, tires, parts, and maintenance, and an average annual mileage for passenger vehicles in 1996 of 11,492 (Highway Statistics); Delucchi estimates national expenditures on maintenance, including in-house government and private fleet maintenance, and sales taxes, but excluding external property damage, divided by national VMT (see Fuel); Runzheimer and FHWA are same as for fuel.

(3) Accidents and Insurance -- BoE assumes $1,000 per year per vehicle for insurance and accidents, divided by average mileage (see Fuel); Delucchi's estimates include insurance administration, accidents paid by users, and pain and suffering "inflicted on oneself," but not external costs; Runzheimer and FHWA same as for Fuel.

(4) Wear and Ownership -- BoE assumes a capital cost of $12,000 over 5 years, and average passenger car mileage (see Fuel); Delucchi estimates private ownership costs, excluding sales tax, divided by total US VMT (see Fuel); Runzheimer and FHWA same as Fuel.

(5) Tolls and Fees -- BoE takes 1996 total toll payments nationally of $4 billion (Highway Statistics) divided by 1996 US VMT of 2,360 (Highway Statistics); Delucchi omits user fees as transfers, so a rate of 1.5 cents per VMT is inserted; Runzheimer estimates registration fees only; FHWA includes parking with tolls, but no adjustment is made here.

(6) Parking -- BoE assumes $1 per day per vehicle for 250 days per year, over 11,492 annual miles (see Maintenance); Delucchi's values combine paid private parking and public parking; Runzheimer provides only a residual "Other" category; FHWA includes tolls with parking.

(7) Time -- BoE uses 60% of US DOT (1997) "personal" wage rate of $17 and 1.2 persons per vehicle at an average speed of 40 mph; Delucchi values time in three categories -- paid time that is delay, paid uncongested time, and unpaid time whether delay or not; neither Runzheimer nor FHWA include time costs, so the Delucchi value is used.

and compiles these into planning and forecasting estimates for business use. Their "intermediate vehicle" is a full size sedan used 20,000 miles per year and traded in after three years.

4. FHWA:[4] Up until 1991, the Federal Highway Administration intermittently contracted for tabulations of cost components for various types of highway

3. Runzheimer International (1997, 1998)
4. Jack Faucett Associates (1991)

passenger vehicles, and published the numbers. The most recent set is based on data collected in Maryland.

The sources and methods for tabulating the various price components are described in the notes to the table.

C.2.5 Determine Which Components Are Included in the "Price"

Several criteria might be considered for defining total price:

1. Out-of-pocket costs: These include fuel, maintenance, parking, tolls, vehicle wear, variable insurance, and other variable costs to the user that are affected by whether a given trip is taken or not.
2. Full, average, or long-run costs: Ownership costs and the annual portion of insurance might be added to out-of-pocket costs.
3. Generalized price: All variable and fixed costs, plus travel time, can be included.
4. Perceived cost: Costs might be limited to those the user explicitly recognizes in making the decision to take a trip or use a vehicle.

Generalized price is used in benefit-cost evaluation of improvement projects for estimating induced demand and associated user costs, especially congestion; such a combined elasticity, however, may be inaccurate because the user does not give each component its dollar-value weight. Pragmatically, the choice of which price to use is also affected by (a) how other elasticities have been measured empirically, for comparison, and (b) how elasticity is used in the model or analytic procedure into which the parameter is inserted.[5] With proper interpretation, different measured elasticities can be used to estimate a generalized price elasticity for modeling that is defined differently from the empirical sources.

Perceived price is an attempt to identify the components of price that are consciously recognized by the user, as a basis for predicting user behavior. Whether making this intermediate variable (perception) explicit adds anything to predictive accuracy is doubtful, and, in any event, it does not provide much guidance for which costs to include. Consumers tend to respond, as a group, to attributes and magnitudes that have some significant impact on their well-being, whether consciously perceived or not.

This means that the user response depends upon what decisions are at stake. If ownership is not in question, then only variable costs may be considered, and more so in the short run. Four alternative definitions for total price are given in Table C-3, ranging from short-run monetary costs to full long-run costs including travel time. The distinction between variable and fixed is not clean: vehicle wear is variable, while ownership is fixed. Insurance is typically paid annually and has a large fixed component, although most exposure to risk is from operation.

5. The HERS model uses a generalized price including time, operating costs, accidents, and user fees, but not parking; demand is aggregated over peak and off-peak (therefore no time diversion) and applies to a single facility (therefore the elasticity allows for route diversion).

C.2.6 Component Shares of Total User Cost

The several definitions of total cost yield a range of component shares, shown in Table C-4. Obviously, the range of values is quite large, depending more upon which total is used than upon the source of data. With travel time being roughly half the cost, its inclusion makes a significant difference.

Table C-4. Component Shares in Total Price.

Component	Low Share	High Share
Fuel	8%	36%
Maintenance	9%	48%
Accidents and Insurance	7%	37%
Vehicle Wear and Ownership	18%	54%
Tolls and Fees	0%	10%
Parking	1%	10%
Travel Time	40%	62%

C.2.7 Empirical Estimates of Own-Price Elasticities

The number of categories drops when considering which components are suitable for empirical estimation, and more so when actual estimates are tabulated. The cost of maintenance is difficult to keep track of, and either controlled or natural experiments are hard to imagine; no such studies were found. User responses to the risk of an accident based on equipment such as air bags have been used to estimate users' implicit valuation of life, but users cannot be observed reducing either their travel or their rate of accidents in response to changes in risk. Tolls, fees, and parking are clearly candidates, but apply to very specific circumstances. Direct estimates of time elasticities have been made, and indirect estimates can be derived from changes in traffic induced by changes in capacity.

Income elasticities are treated as exogenous for purposes of estimating travel demand elasticities, by assuming that price changes are not large enough or general enough to result in a significant change in income for the average traveler.

C.2.8 Magnitudes of the Shrinkages

The size of the shrinkage factor (σ in Equation C.4) for fuel can be seen in Goodwin's (1992) review of elasticity estimates. Table C-5 summarizes his result for studies based on fuel price changes. The numbers are juxtaposed to permit comparison of elasticities of fuel consumption (average of over 100 separate empirical values) versus elasticities of travel (about a dozen numbers), stratified by whether a time series model or a cross-sectional model was used and whether the intent was short term, long term, or ambiguous.

Long term elasticity estimates tend to be at least twice as large as short term values, as might be expected. For fuel, the shrinkage from fuel consumption to travel consump-

Table C-5. Goodwin's Review of Fuel Price Elasticities.

Method	Fuel or Travel	Short Run	Long Run	Uncertain
Time-series	**fuel consumption**	-.27	-.71	-.53
	travel demand	-.16	-.33	-.46
Cross-section	**fuel consumption**	-.28	-.84	-.18
	travel demand	n/a	.29	-0.5

Source: Goodwin (1992).

tion seems to be about 0.5 to 0.9, meaning that half to ninety percent of the reduction in fuel expenditure is the result of less travel.

For other price components, the shrinkage factor is more speculative. Increases in insurance and vehicle ownership costs might result in fewer vehicles but more mileage per vehicle, with the latter less than fully offsetting the former. Deterioration in pavement quality increases wear and tear, reduces fuel mileage, and reduces speeds. Increases in tolls directly affect the cost per vehicle mile, but, depending upon how the tolls are graduated, could alter the mix of vehicles and the time-of-day distribution.

The largest user response is likely to come from those users for whom the price change is relatively largest. A fuel price or tax increase will affect long trips and vehicles with low fuel efficiency; insurance costs deter ownership in urban areas thereby shifting the geographic distribution of vehicles; high parking costs deter short trips more than long ones; high ownership or insurance costs deter vehicles with low annual utilization. Explicit shrinkage factors are not estimated for these components.

C.2.9 Durations of the Short-and Long-Run Adjustment Periods

Some responses occur within days or weeks, while others may take five or ten years to reach equilibrium. To usefully interpret an empirical elasticity estimate, the time dimension must be known. If the statistical measure for an empirical estimate includes all VMT or other changes that occurred within a year of the price change, then a short-run elasticity has been estimated. Longer lag periods for the same price changes yield longer run elasticities, but separating behavioral responses from background variation becomes increasingly difficult.

Several studies reviewed by Cairns, et al. (1998) reveal the degree to which individuals change their travel patterns on a daily basis. Two studies, summarized in Table C-6, are illustrative. Of a group of commuters passing a given point on a road on a given day, 60% could be found a week later within the same 2-hour block; the rest were doing something slightly or completely different. A similar study with a longer time lag showed a smaller share doing the same thing. Other studies reinforce the same conclusion: individual travel variability is high on a day-to-day basis, and more so over longer time spans. This is without any significant changes in either exogenous or endogenous factors.

One implication is that—if stability is much higher in the aggregate than in the microscopic—attempting to predict individual travel behavior is less fruitful than using

Table C-6. Travel Behavior Variability

Location: Time Lag: Type of Travel:	Leeds 1 Week commuting	Southampton 4 months regular trips
Same behavior[a]	60%	49%
Different time	7%	5%
Different route	14%	7%
Different mode	8%	1%
Different destination	5%	13%
No trip/different trip	6%	25%

Source: Cairns, et al. (1998).
[a] travelled the same route by car within the same 2-hour time period.

aggregate elasticities for endogenous changes. Another is that, with so many individuals making changes within a short time span, the responses of travelers to changed conditions is likely to be rapid. There is not a lot of inertia in travel patterns. According to Cairns, et al. (1998), roughly 50% of the response to a change takes place within 1 to 3 years, and 90% within 5 to 10 years. Hence, long-run elasticities tend to be about twice as large as 1-year or short-run elasticities.

C.3 Conversion to Generalized Price Elasticity

The results of the above process are displayed in Table C-7, showing empirical estimates of component travel elasticities, along with their implied short- and long-run total travel demand elasticities. The range of possible values is wide, extending from -0.22 to -3.7 for short-run demand and -0.57 to -5.1 for long-run demand. The most plausible numbers, however, lie in the -0.5 to -1.0 range for short-run demand, and -1.0 to -2.0 for long-run demand. These elasticities apply to *vehicle* travel, not person travel, which can be considerably less elastic and still be consistent with these vehicle elasticities due to changes in vehicle occupancy and other adaptations.[6] The "high" values come from using the full generalized price as the base in Equation C.5., while the "low" values come from using subsets such as variable costs.

C.3.1 Fuel Price Elasticities

Numerous empirical studies have estimated the price elasticity of gasoline, and a few have measured the travel elasticity with respect to fuel price. The review and summary by Goodwin described above reflects the results of these studies, and subsequent studies have tended to confirm his conclusions. Thus a value of -0.16 for short-run travel impacts of fuel price changes and -0.33 for long-run impacts are used, with Equation C.5, in Table C-7.

6. Cairns, et al. (1998) provide an illuminating list of examples that illustrate the many ways in which individuals and households can satisfy their travel requirements while reducing vehicle miles of travel.

Table C-7. Component and Total Travel Demand Elasticities

	Component Elasticities		Implicit Total Travel Elasticities			
			Low		High	
User Cost Component	**SRE**	**LRE**	**SRE**	**LRE**	**SRE**	**LRE**
Fuel	-0.17	-0.33	-0.48	-0.93	-2.0	-3.9
Wear and Ownership	-0.12	-0.31	-0.22	-0.57	-0.6	-1.7
Tolls	-0.10	-0.31	-0.33	-1.03	-1.0	-3.1
Parking	-0.15		-1.17	-1.61	-3.7	-5.1
Time	-0.38	-0.68	-0.60	-1.07	-0.9	-1.7

C.3.2 Ownership Elasticity

Holding exogenous factors constant, an increase in the real price of vehicles of the same quality causes a reduction in the purchases of vehicles, especially new ones. The most likely behavior response is to defer purchase of a new or better vehicle, and keep using the old one. If, however, the response is measured in the aggregate as total vehicle ownership, then fewer vehicles means less VMT, offset by the extent to which vehicles are shared.

Dargay (1998) compared several ownership and operation elasticities between the UK and France, including price elasticity and income elasticity. Converting the price elasticities to VMT elasticities, using a shrinkage factor of 0.9 and the values from Table C-4 in Equation C.5, provides the results shown in Table C-7. The source of imprecision in applying ownership elasticities is the uncertain share of total cost per VMT comprised by ownership and wear-and-tear costs.

C.3.3 Toll Elasticities

Elasticities in response to toll variations are difficult to impute because the quality of travel, in terms of delay and total travel time, often changes when the toll changes. First consider the case of a change in a flat rate toll, for example, a toll increase of $2 to $3 over the entire day. In this instance, the traveler must consider trade-offs between paying the higher toll and:

1. Changing route to a free, but most likely slower, alternative route.
2. Abandoning the trip.
3. Carpooling to share the toll or taking transit to avoid the toll. Thus, giving up the freedom of being a single occupant vehicle and, likely, increasing the total trip time.

Therefore, considerations include a trade-off between a longer trip or paying the increased toll (value of time) and the trade-off between money and travel (price elasticity). Many empirical estimates of flat rate toll price elasticities in the U.S. have found elasticities generally ranging from -0.1 to -0.31.[7]

Next, the case of variable toll rates, where the toll varies by time of day or congestion level, is examined. In this case, tolls are generally greater during periods of peak traffic demand. Assuming congested conditions during the peak period, travelers must consider a trade-off between their preferred time of travel or traveling at an alternate time but paying a reduced toll (time elasticity) plus experiencing reduced delay (value of time).

The empirical evidence regarding driver response to variable tolls is limited and subject to considerable variation based on the specific opportunities available to avoid the toll. For example, some facilities that offer a variable toll are situated in the median of a free route and, therefore, altering travel route to avoid the toll is relatively easy. Other facilities offer discounts or free trips to high occupancy vehicles, increasing the benefit of sharing a ride over and above simply splitting the toll between vehicle occupants. Therefore, it was not surprising that elasticities found in the cases with variable toll rates had a wider variation that flat toll rates and were generally larger. They typically ranged from -0.02 to -1.0 (see Table C-8).

Table C-8. Toll Price Elasticities on Facilities with Variable Toll Rates

Location	Elasticity	Source
Lee County (Cape Coral and Midpoint Bridges)	-0.02 to -0.36	Cain, Burris, and Pendyala (2001)
California (SR 91)	-0.9 to -1.0 -0.7 to -0.8	Sullivan, 2000; Jan, Small, and Sullivan (2002)
California (I-15)	-0.02 to -0.16 -0.34 to -0.42	Dahlgren (1999); San Diego Association of Governments (1999)
Singapore (City Center)	-0.25	Menon, Lam, and Fan (1993)
France (A-1)	-0.16 to -0.28	Small and Gomez-Ibanez (1997)
Houston (Hardy Toll Road)	-0.4 to -0.8	Spock (1998)

Since this effort is focused on changes in VMT and not on the time of travel, the elasticities found for flat rate toll are used in developing a total travel demand elasticity. Because most trips are not tolled, national averages of tolls per VMT are not useful. Of trips that are tolled, $1.25 might be about average, yielding a share of total costs on a 15-mile trip ranging from 10-30%. This range is used in Table C-7 instead of the range shown in Table C-4 on page C-11.

C.3.4 Parking Price Elasticities

Shoup (1994), and Willson and Shoup (1990) review more than a dozen studies of parking pricing, including their own as well as Shoup and Pickrell (1980). From these studies it is possible to extract five case studies that provide sufficient data to construct ordinary price elasticities. In all of these examples, the price of parking was zero for the base alternative in the comparison, so the calculations in Table C-9 base the elasticity estimates on an assumed total price for travel, rather than for parking

7. Wuestefeld and Regan (1981); Harvey (1994); Wilbur Smith Associates (1995); Gifford and Talkington (1996); Samuel (2000). Samuel uses a phased-in toll increase on the Ohio Turnpike to make a back-of-the envelope calculation of trip elasticity of -0.23 and VMT elasticity of -0.15, in his *Toll Roads Newsletter* for February, 2000.

alone. The elasticity magnitudes are large even when the price change is measured against only a small share of long-run cost.

Table C-9. Parking Total Price Elasticities

	Trip Rate[a]		Parking Price[b]		Total Price Elasticity[c]	
Before/After Case Studies:	**Free**	**Priced**	**Free**	**Priced**	**Low**	**High**
Mid Wilshire, LA	48	30	0	58	-1.05	-3.33
Warner Center, LA	92	64	0	30	-1.65	-5.23
Ottawa CBD, Canada	94	80	0	30	-0.81	-2.56
Average					-1.17	-3.70
With/Without Case Studies:						
Century City, LA	39	32	0	23	-1.27	-4.02
Civic Center, LA	78	50	0	30	-1.95	-6.16
Average					-1.61	-5.09

Notes:
a Autos driven per 100 employees.
b Price in dollars per month.
c Full vehicle "backward" arc (low price to high) price elasticity based on 35-mile round trip average for LA reported in Willson and Shoup (1990), at an average user cost of $.22 per VMT for variable costs only (=$163 per month for the Low estimate) or $.70 for all costs including time but excluding parking (=$515 for the High estimate). Backward elasticities are lower than midpoint or forward arc elasticities for downward-sloping demand curves.

In the before/after case studies, the price of parking changed at a particular work site, and the behavior responses were tracked for up to a year after parking became priced. Some of the employers had ridesharing incentive programs, which were ineffective so long as parking was free. These examples are interpreted as representative of short-run demand elasticities. The with/without case studies compare similar work sites, one priced and one not. These are interpreted here as long-run elasticities, on the rationale that commuters had sufficient time to make long run adjustments. These elasticities would be higher if all employee parking were priced, because more people at more sites would be seeking ridesharing or transit arrangements.

Because parking is free to the user for 99% of all trips (over 90% of urban work trips), the average share of parking in the cost of travel to the user is not a valid base value for these elasticities. As Shoup (1994) states,

> "It is important to remember that the elasticity estimates [average 0.15] refer to commuter response to changes in only the parking price of their trip and are therefore smaller than the elasticity of demand with respect to changes in the full price of automobile trips."(p. 159)

He gives other reasons why these estimates are low, including the likely availability of cheaper parking nearby and the inelasticity of work trip demand.[8]

8. Harvey (1994) offers examples from San Francisco and Boston airport parking, which are consistent with Shoup's summary if Harvey's elasticities measure the number of vehicles parking. This does not necessarily equate, however, to the same percentage reduction in VMT, because some of the deterred parking is shifted to taxi trips.

C.3.5 Time Cost Elasticities

Several studies have tabulated traffic volumes subsequent to an increase in capacity, or occasionally in response to a decrease in capacity or change in travel time. For those based on change in capacity, the measure of elasticity is

$$e_{T,\,capacity} = \frac{\%\Delta VMT}{\%\Delta cap} \qquad \textbf{\textit{Eq. C.6}}$$

where$\%\Delta cap$ = percent change in capacity, with capacity measured in lane miles. Hansen et al. (1993) estimate this elasticity for eighteen highway sections in California, and include controls for trend VMT. To transform this measure into a price elasticity requires substituting a price measure for the capacity measure, such that

$$e_T = \frac{\%\Delta VMT}{\%\Delta p} = \frac{\%\Delta VMT}{\%\Delta cap} \times \frac{\%\Delta cap}{\%\Delta p} = e_{T,\,capacity} \times \frac{\%\Delta cap}{\%\Delta p} \qquad \textbf{\textit{Eq. C.7}}$$

i.e., a conversion factor is needed from the Hansen elasticity to a price elasticity, consisting of the ratio of an increase in capacity to its corresponding reduction in price. Taking time as the only component affected, the question is what are the time savings from a given added capacity? Most of Hansen's expansions are from four to six lanes or six to eight lanes; if it is assumed that two lanes in the same direction are congested, and that adding a third will increase average speed from 40 to 60 mph[9] for at least a few years, then a 50% capacity increase is equivalent to a 33% time savings (neither the value of time nor occupancy affect this result), for a conversion factor of -1.5. Thus Hansen's low or short-run value of about 0.25 becomes -0.375 and his high or long-run value of 0.45 becomes -0.675.

Cohen (1995) reviews several time-travel elasticity studies, whose results are somewhat erratic, but generally consistent with the above. Often, some types of induced traffic are counted (e.g., new travel by users already in the market) and others omitted (e.g., route diversions). Unlike other components of user price, time cannot be economized by sharing the cost among additional vehicle occupants. Therefore, elasticity with respect to time cost should be lower than for the components whose cost can be shared among passengers.

C.4 Adjustment from Total to Section Elasticities

The total price elasticity reflects the change in vehicle miles of travel in response to the generalized price of travel. For application to the specific context of evaluating improvement alternatives for a section of highway, the elasticity for price changes on the section requires several adjustments. In this context, the price is the generalized price per vehicle mile of travel, and the quantity is the volume of vehicle travel on the facility, per hour or per day.[10]

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9. This speed change implies an average savings of 0.50 minutes per VMT. Using the HERS (Chapter 6) delay equations for expressways, which model average daily delay per VMT as a function of AADT/c(apacity), a 50% increase in capacity at an AADT/c of 15 (fairly high) results in delay savings of 0.855 minutes per mile, whereas an initial AADT/c of 12 yields a savings of 0.255 per mile.
10. A possibly superior way to calculate section elasticity is to base it on trips over the section rather than VMT. This automatically incorporates the length of the section. In HERS, the elasticity is applied per VMT but adjusted for section length.

C.4.1 Occupancy

Any price component that applies to the vehicle and can be divided among occupants creates an incentive to increase occupancy; such monetary components include tolls, excise taxes, wear and ownership costs, parking, and operating costs except for some portion of accidents.[11] The remaining non-divisible non-monetary price components are time and collective accident costs. Thus empirical evidence should show higher observed elasticities for monetary components than non-monetary, other things being equal. A strong pattern is not evident from Table C-7, although at the high end the time elasticity is lower than all but wear-ownership.[12]

Conceptually, the overall total price elasticity has two components, one derived from the divisible portion of the price, the other from the indivisible portion. Using Figure C-3, the elasticity at a point p_0, v_0 can be represented as the slope of a demand curve.[13] The less elastic demand is labeled D_{nd} (although we are dealing with point elasticities, the explanation is easier if we imagine them as arc elasticities).

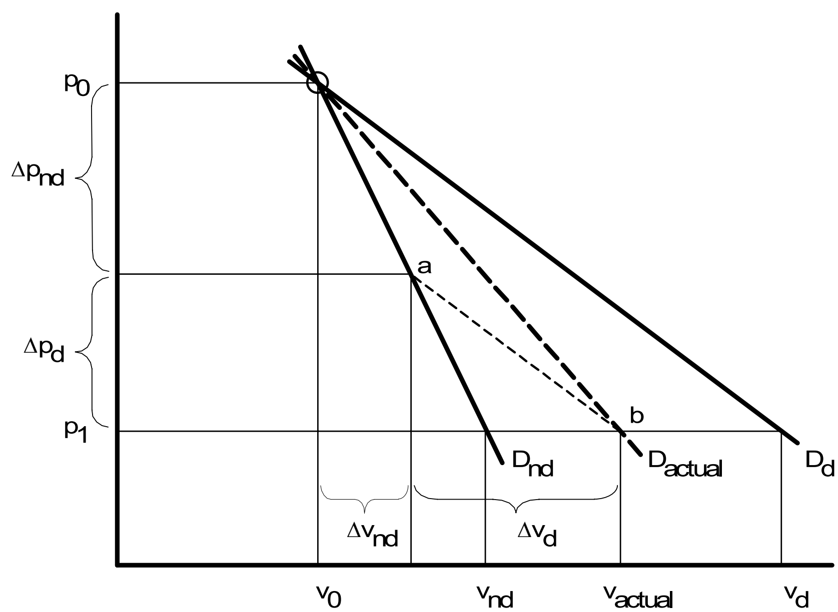

Figure C-3. Elasticity decomposition into divisible and non-divisible portions.

If all price components were indivisible, there would be no incentive for increased occupancy, so elasticity would be relatively low; for a given price change from p_0 to p_1, the additional traffic would be from v_0 to v_{nd}. Alternatively, if all price components were monetized to the vehicle and divisible among occupants, the applicable demand curve would be D_d and the induced traffic would be from v_0 to v_d. More gen-

11. Insurance rates are often higher for carpool drivers, but the component is probably shareable in the same way operating costs can be shared. Damages to the vehicle and other property can be divided, but all occupants are exposed to risk of personal injury and fatality if the vehicle is involved in a crash.
12. An increase in the money share of the generalized price -- assuming a mix of travelers with differing values of time -- will shift the mix of travelers toward those with higher time values. We do not know, however, if the demand elasticity of high income travelers with respect to the *generalized* price is higher or lower than that of low income travelers.
13. Holding constant the initial point, the elasticity varies directly with the slope, as can be seen in **[C.1]**.

erally, where the components are mixed, the demand curve is a weighted average, represented by the dashed demand D_{actual}. The end result at point b can be decomposed into a movement along D_{nd} for the non-divisible portion, plus a movement along line ab (parallel to D_d) for the divisible portion. Hence the incremental volume from v_0 to v_{actual} is comprised of a portion Δv_{nd} from non-divisible price components, plus a portion Δv_d from the divisible components. The share of movement along D_{nd} versus D_d is determined by the shares of price components, Δp_{nd} and Δp_d.

In elasticity terms, the actual or combined elasticity is simply a weighted average of the two component elasticities,

$$e = \eta e_{nd} + (1 - \eta) e_d \qquad \textbf{\textit{Eq. C.8}}$$

where η = share of generalized price that consists of non-divisible components, e_{nd} = elasticity for non-divisible components, e_d = elasticity for divisible components, and e = combined or "actual" elasticity.

Neither of the "pure" (all non-divisible or all money) demand curves can be observed directly, and although there may be enough variation in the distribution η to extract the two elasticities econometrically, whatever evidence has been acquired has not been studied in this way.[14] If it can be assumed that e_{nd} and e_d are proportionally related, then

$$e_d = (1 + x) e_{nd} \qquad \textbf{\textit{Eq. C.9}}$$

where x = fraction by which the more elastic divisible-price demand is greater in magnitude than the non-divisible demand.

In responding to a change in the generalized price of highway travel, the total price elasticity incorporates changes in vehicle trips due to changes in mode or occupancy, change in destination or trip chaining that alter trip length, and adding or deleting person-trips (it omits route and temporal diversion). Using Table C-3 and averaging values, the share of existing price that is monetary is about one-half.[15] The portion of total elasticity that is due to occupancy is unknown, but might likely be around one-third, for a value of x of 0.5. This is enough information to calculate the two divisible/non-divisible elasticities, given an initial overall elasticity, as shown in Table C-10.

If the share of the price that consists of divisible components remains fixed, nothing is gained by this decomposition. If, however, specific sections are priced differently from the overall average, or the intent is to test a different pricing policy, then the component elasticities can be recalculated based on price components that pertain to the particular section. The example shown in Table C-10 might represent a shift to congestion pricing, such that delay is almost eliminated but the money price is much higher. The result is a large decline in the non-divisible costs, but only a modest increase in average elasticity.

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14. Average vehicle occupancies vary by trip purpose from barely one to over three, as evidenced by FHWA (1992) or MTC(1998); the effect on average occupancy of current variations in the divisible money price is likely to be much smaller in magnitude, thus hard to detect empirically.
15. This result gives half as much weight to the Runzheimer column, on the assumption that these data apply primarily to business travel.

C.4.2 Section Length

Most traffic on a given section of highway can be assumed to be using more than that section to accomplish its trips. If, for example, the price for the section being evaluated will decrease by 20% if the improvement is implemented, and the section constitutes 60% of the complete vehicle trip, then the price for the trip will decline by 20% times 60%, or 12%. If total elasticity for the vehicle trip is -1.0, the elasticity for the section is 60% of the total, or -0.6; the 20% price decrease will thus result in a 12% reduction in volume, same as if the price change were calculated for the full trip and applied to the -1.0 elasticity. Specifically,

$$e_s = e\frac{L_s}{L_T} \qquad \textbf{\textit{Eq. C.10}}$$

where e_s = section elasticity, e = total price elasticity, adjusted for occupancy, L_s = section length, and L_T = average trip length for vehicles using the section.

Table C-10. Occupancy Elasticity Based on Divisible Price Components

total vehicle price elasticity (base elasticity)	-1.00
Occupancy elasticity:	
share of base price that is nondivisible (%) (η)	50%
elasticity increment for divisible price (%) (x)	50%
elasticity for nondivisible price components (e_{nd})	-0.8
elasticity for divisible price (e_d)	-1.2
section-specific data:	
money price	0.20
operating costs	0.26
accidents	0.10
normal travel time	0.30
delay	0.02
Total	0.88
nondivisible portion of price (η)	0.37
base elasticity adjusted for divisible/nondivisible components	-1.05

If the section is longer than the average trip length, then the multiplier should be one, assuming that the price change on the section applies to the full trip for the average traveler on the section. Individual trips that use only part of the section would show a lower elasticity (approaching zero), but there would be several or many of them in each average daily VMT across the entire section, giving the same result as if a single trip used the entire section.

C.4.3 Route Diversion

For most of the components of the generalized price of vehicle travel, route diversion is not an available substitute (e.g., fuel price, operating cost). For the parking studies, employee parking at a substitute destination is not feasible. Toll elasticities of major facilities such as the Golden Gate Bridge incorporate very few alternative route possibilities, and time elasticities based on facility expansion allow for some indeterminate amount of diversion in the empirical values. Thus the elasticity for a single facility or section will be higher than the value derived from empirical estimates for total price elasticity, because travelers can divert to parallel routes.

The magnitude of an elasticity is greater if there are many close substitutes. A route diversion elasticity will be high if there are alternative routes that are only slightly "worse" in the sense of having a higher generalized price. For example, a simplified representation of route diversion is shown in Figure C-4. The section being considered for improved is S_0. In the base case, the preferred path for a trip between A and B uses the section S_1, but an alternative route uses S_{a1}, S_0, and S_{a2}. The alternate might become preferred if S_0 were improved to the extent that the total trip price were lower via the alternative route, i.e., if

$$p_{a1} + p_0 + p_{a2} < p_1 \qquad \textbf{\textit{Eq. C.11}}$$

where p_i = generalized price on section S_i. Sections S_{a1} and S_{a2} are "access" sections that would be used to get to and from the improved section. For a given primary section of interest, S_0, there might be many trip ends such as A and B that do not use S_0 as their preferred route, but might choose to do so if the price on S_0 were lower, e.g., faster.

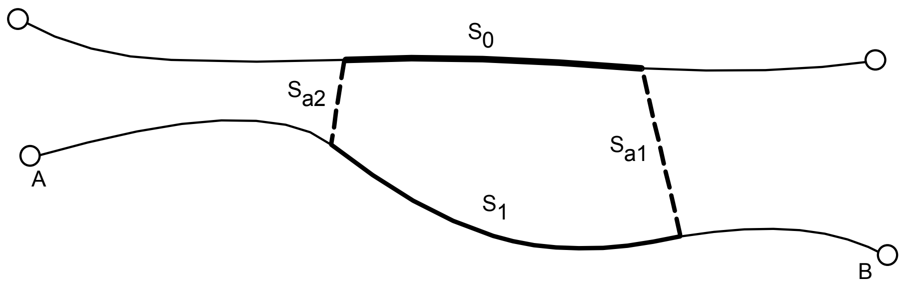

Figure C-4. Generic example of route diversion.

The demand elasticity on S_0 with respect to route diversion only depends upon the relative volumes of traffic on the two routes (as well as other alternate routes) and the difference in the price between them. If v represents the volume on all routes such as S_1 that do *not* use S_0 but could, stated as a ratio to the volume on S_0, then

$$\text{liversion elasticity } (S_0) = \angle\left(\frac{s \times v \times V_0 / V_0}{r/a}\right) = \angle\frac{svc}{r} \qquad \textbf{\textit{Eq. C.12}}$$

where s = share of corridor traffic not using S_0 for which the price of S_0 is r% greater than their preferred route, a = the access share of the alternative route that incorporates S_0, and V_0 is the volume on S_0. The numerator is the percent change in volume on S_0 from a change in price of on S_0, and the denominator is the percent change in the price of the alternate route from a change of r% on S_0.

None of these parameters is readily observable, although they could be extracted from traffic assignment simulations. As an example, parameter values have been entered into Table C-11 and the diversion elasticity calculated. There exists some distribution of the share of traffic in the corridor according to the percentage by which the price of the preferred path differs from the path that incorporates S_0, and an example distribution is shown in its cumulative form. Because its shape is unknown, it is possible (and likely) that the elasticity on S_0 varies by the magnitude of the percentage price change on S_0, i.e., the diversion elasticity is not a constant. In general, it might be expected that network redundancy is higher in urban areas, implying that route diversion elasticities are higher (in absolute magnitude) in urban areas.

Table C-11. Construction of route diversion elasticity

% by which route with section S_0 is worse than preferred path (*r*)	0.05	0.1	0.2	0.4	0.5
cumulative share of ROTC within % of trip cost (urban) (*s*)	0.10	0.25	0.50	0.85	0.95
ratio of ROTC volume to section AADT (trips) (*v*)	0.60				
access share of price (*a*)	0.50				
percent increase on section S_0	0.06	0.15	0.30	0.51	0.57
diversion elasticity	-0.60	-0.75	-0.75	-0.64	-0.57

ROTC = trips in the rest of the corridor that do not use the primary section but could.

The diversion elasticity can be added to the previous total elasticity that has been adjusted for section length and occupancy. Because the section length relative to the total trip length is corrected for separately, section length does not need to be considered for route diversion.[16] Also, because speed-volume or delay functions account for the increase in price from congestion, the capacity of S_0 does not need to be considered in diversion.

C.4.4 Time-of-day Diversion (Peak Spreading)

A price component that applies only to the peak should have a higher elasticity than that for the total price as estimated from the empirical evidence, considering only the peak period, because some travel will be diverted to the off-peak. If diurnal demand periods are modeled separately (i.e., two or more demand periods per day), then the interrelationships among the demand periods must be explicitly modeled. This is more than just a problem of elasticities.[17] Of narrower interest here is whether peak-offpeak price differentiation alters the overall—or daily—elasticity. The bottleneck model provides an example of a substitution of price for queuing delay, without any change in overall traffic, but the model does not include the option of changing the total number of trips.

If the price varies over the time of day according to the level of demand, then overall delay will be reduced (relative to no differentiation) by redistributing traffic from congested periods to time periods with lower v/c ratios. This suggests that total traffic levels will be higher because the average price is lower. If, however, we hold average price constant as well as the share that is monetary, it is not obvious that the demand elasticity is changed by altering the price between peak and offpeak.

Two effects can be separated: first, the change in volumes between a differentiated price and a constant price; and second, whether the elasticity is different for total demand if the price is differentiated or constant.

16. A very short section might have negligible impact on generating new trips but still have a large diversion impact. If the section were isolated, then the access portions of the diversion would neutralize any diversion, but if the access were easy (e.g., turn right on one block rather than the next), the amount of diversion could be large. The benefits from this diversion might be small in absolute terms, but so might the costs. Incremental consumer surplus would be made up almost entirely of diverted (rather than new) trips.
17. Some of the difficulties are described in Cambridge Systematics (1997).

Because the share of the price that is paid in money is recognized in the occupancy factor, for purposes of peak spreading the price can be treated as a single dimension. Empirical evidence on peak spreading applies to a context in which peak and offpeak prices are differentiated only by the amount of delay. If we imagine a case with the same demand curves but constant price across all (both) periods, and the same average price, then more demand will occur in the peak and less in the offpeak. If elasticities differ between the two periods, then total volume will be higher if peak elasticity is greater then offpeak, and lower if the reverse.

If we then ask what difference this makes for total price elasticity, the simplest answer is that it makes no difference if the two elasticities are the same. If we use constant elasticity demand curves, located at different volume points but having the same elasticity, then the overall elasticity is not affected by the differentiation of price between the two periods, for the same average price.

If the elasticities are different between the two periods, then the amount of differentiation between peak and offpeak prices may cause the aggregate elasticity to be greater or lesser than the case where the price is constant, but the effect seems to be relatively small.[18]

C.5 Conclusions

Despite the widely varying orientations, data sources, and scope of applicable empirical studies, and the fact that none was attempting to estimate generalized-price travel demand elasticity, the results are roughly consistent. Users respond to changes in any of the components of travel cost that are measurable, and the response starts immediately and continues over many years.

Taking the short run to be approximately a year or less, vehicle demand-price elasticity tends to fall in the range of -0.5 to -1.0, with -0.7 to -0.8 being the most likely for typical conditions. The long run may occur over twenty years, but five years is enough to cover most of the effects. Long run elasticities are about twice as high as short run, with a range of about -1.0 to -2.0. Response to variable and obvious money costs such as parking and fuel show higher elasticities than for fixed and more hidden costs. These elasticities apply to vehicle-trips, not person-trips.

These total price elasticities can be applied to specific highway sections, adjusting for changes in the share of divisible price components, the section length, and possibilities for route diversion. The elasticity values are somewhat uncertain, due to the fact that every context is different, but the uncertainty could be reduced with focused data collection and research.

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Appendix D:

Basic Theory of Highway Project Evaluation

Douglass B. Lee, Jr.[1]

The criterion for making good investments is to select projects for which the net benefits are positive, i.e., incremental benefits exceed incremental costs. The major analytic steps are: define alternatives, evaluate impacts, and select the project with highest net benefits. If pricing is determined independently of marginal cost, however, pricing is exogenous and the investment evaluation is necessarily in a second-best mode.

The HERS model incorporates demand elasticity and benefit-cost evaluation principles that are specific to the investment and policy alternatives typically considered at national and local levels. As highway investment concerns shift, the HERS model attempts to adapt by making explicit the variables and relationships that will permit the model to realistically address the new concerns. In doing so, the model becomes more general in its scope and more flexible in its application to questions of interest.

For the 1997 *Conditions and Performance* report to Congress, the HERS model was extended to utilize demand elasticities, such that highway improvements that lowered or raised user costs could lead to changes in travel volumes, and that over the long run the effects of improvements could be to shift the demand curve from where it might have been placed in initial forecasts (see Appendix B, “Induced Traffic and Induced Demand” and Appendix C, “Demand Elasticities for Highway Travel”). Also, HERS was modified to estimate and take into account emissions of air pollutants, although the feature was not turned on until the 1999 report to Congress. More recently, HERS has been modified to incorporate a money price that is separate from user time and operating costs. Fuel taxes and tolls are therefore recognized, both in estimating demand and as potential policy instruments such as for congestion pricing. Thus the principles outlined in this Appendix have served as a guide in developing the economic portions of the model, and the model now embodies them to a large degree.

D.1 Project Description

A physical facility can be represented for evaluation purposes by its unit costs with respect to traffic volume, measured as vehicle trips per hour. Three functions of volume provide the information necessary for calculating net operating benefits: average variable cost (*AVC*), marginal cost (*MC*), and price. Assuming a base alternative and one project alternative, the physical characteristics of each alternative are given by

1. The author thanks E. Ross Crichton and Anthony Rufolo for helpful comments on a previous draft.

their variable cost curves, while the price curve constitutes the policies affecting how the facility is operated. All variable costs, whether monetized or not, are included. Cost and price components are assumed to be converted into a common numeraire (dollars), referred to as generalized cost or generalized price, meaning that it combines money and in-kind components on the same scale. Neither fixed costs nor fixed charges (e.g., annual vehicle license) are represented in the diagrams.

In general, at any given volume, marginal cost, average variable cost, and price to the user are all different. *MC* and *AVC* are mathematically related, and will diverge if any component of cost varies with volume (or *v*/*c*), i.e., *MC* is unequal to *AVC* if unit cost (*AVC*) goes up or down with volume. Because unit travel time costs rise with congestion, for most volume levels marginal cost lies above average cost. Price includes user charges, which are transfers and not costs, and excludes externalities and agency costs (facility wear, maintenance, and operation), which are costs that are not part of the price.

D.1.1 Marginal Cost

The marginal social cost curve is the guide for efficient pricing, so if $p = MC$ at all volumes, then net benefits in the short run are maximized for the facility. In this special (first-best) case, price and marginal cost are the same. As shown more generally in Figure D-1, price, represented by the price function, is not directly tied to marginal cost, labeled *MC*. Since the price function determines the quantity demanded by its intersection with the demand curve, actual volume is q_0 at a price of *p*, with a marginal cost of *mc* and an average cost of *ac*. The inefficiency from not pricing at marginal cost is given by the triangular area bounded by p_{mc}, *mc*, and *p*.[2]

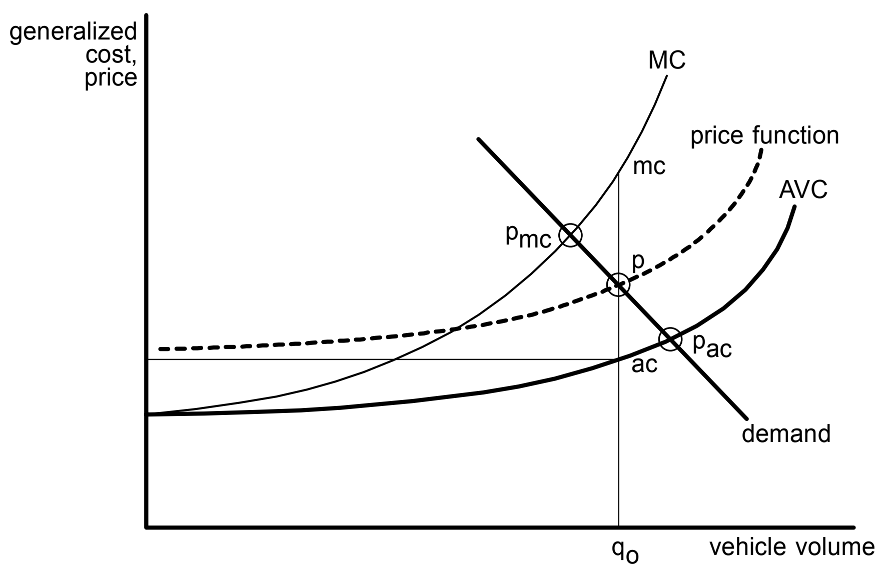

Figure D-1. Three Functions of Trip Volume.

2. The welfare loss from inefficient pricing does not enter in to the measurement of second-best benefits, but recognition of the inefficiency provides some insights when comparing second-best benefits to first-best pricing.

D.1.2 Average Cost

Variable social costs include travel time, fuel, accidents, other vehicle wear and operating costs, damage from emissions and noise, and facility wear, maintenance, and operation (agency costs), but not fuel taxes or tolls. They are variable because they increase with vehicle miles traveled. Their combined average unit cost per vehicle mile (*AVC*) might rise, decline, or remain constant with volume, which is a rate of flow. In fact, most of the components of variable cost vary slightly with volume, due to congestion, but the one that varies by far the most is travel time.

Because users are faced with the average rather than the marginal cost of travel time, it is frequently assumed that price and average cost are the same, but this usually is not true because of user charges, agency costs, and externalities. The *AVC* and *MC* functions are mathematically related, such that either one could be derived from the other, but it is the components of average cost that can be observed empirically.

Total variable cost can be measured either as the area under the marginal cost curve (e.g., up to q_0) or as the average variable cost (*ac*) times the volume (q_0), the latter being a rectangle, as shown in Figure D-1. This relationship will be used later.

D.1.3 Price

Price is the cost to the user, and includes travel time, accidents, and operating costs as well as money payments that vary with usage. The price function in Figure D-1 assumes that travel time is the main reason the generalized price varies with volume; user charges are approximately constant per vehicle mile, such as through a fuel tax.

The price function in this diagram is shown as lying above average cost. This might be the case if variable user charges exceed variable externalities and agency costs. If the reverse is true, then the price function lies below *AVC*, as shown in Figure D-2. The same relationships hold as before, although the inefficiency triangle is relatively larger. For congested conditions, it is unlikely that price will be above *MC* without a congestion-related toll, but price could be above *AVC*. Whether price is above or below *AC* depends upon the magnitude and valuation of externalities and agency costs relative to user charges.

Thus volume could be determined by any of the three functions, shown at the circled points in Figure D-1 or Figure D-2: by marginal cost at p_{mc}, for efficient pricing and first-best evaluation; by average variable cost at p_{ac}, which ignores actual user charges, agency costs, and externalities; or by the price function at *p*, which is the most general case.

D.1.4 Constructing the Demand Curve

The demand curve shows the quantity that will be taken by consumers across a range of prices, generalized to include time and running costs. In reality, this demand curve is constantly shifting, affected by user preferences as well as their knowledge of what conditions will actually pertain at their time of usage. For analytic purposes, the demand curve is assumed to be fixed—or represented by some average—for some period of time. An example of a demand period is the AM peak period, lasting several hours in larger urban areas. A single demand curve might represent the AM peak, or

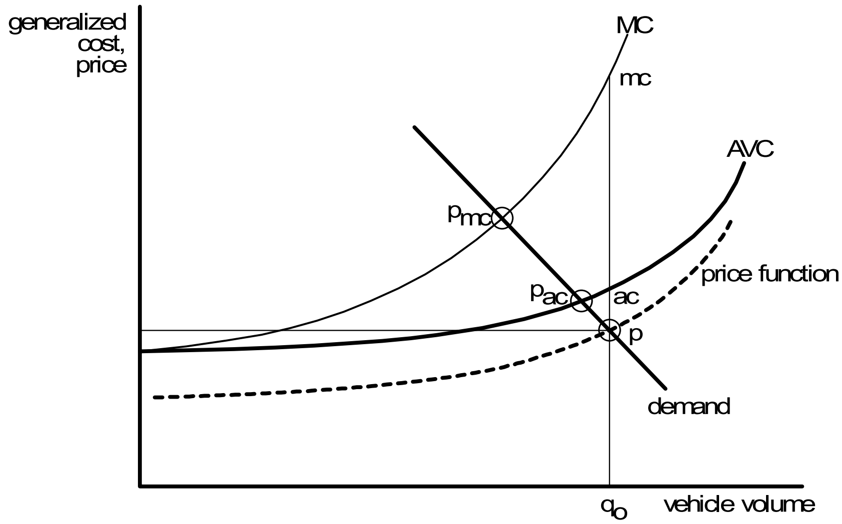

Figure D-2. Three Functions with Price Below *AC*.

the AM and PM peaks combined; time periods do not need to be contiguous to be treated as a single demand period.

The minimum information needed to construct a demand curve is a price, a quantity, and an elasticity at that point. The price could be the average generalized price during peak periods, namely, the sum of travel time, running costs, and user fees representative of peak times.[3] The quantity is the average traffic volume for the peak, in vehicles per hour. An elasticity can be selected by comparing the project to other facilities with respect to the mix of components of price, the substitutes available, and the types of vehicles and trip purposes. Ideally, the elasticity should be compatible with the nature of the project, e.g., include diversions if the project is a single facility. The demand curve could be disaggregated into separate analyses for each market segment (e.g., trucks, commuters, recreational travelers), but some averaging is always necessary. A single demand curve for all users is assumed here.

With a single elasticity value, the functional form of the demand curve can be either straight line or constant elasticity. Given the demand point (p, q_0) in Figure D-2, only one demand curve of each type passes through that point with the given elasticity at that point. A straight line is used here.

D.1.5 Project Alternatives

To evaluate a project, a set of curves is needed for each of the base and the project alternatives, as shown in Figure D-3. Data for the base alternative are designated with a "0" subscript, and with a "1" for the project alternative.

The marginal and average cost functions are characteristics of the facility, resulting from its capacity, geometrics, terrain, pavement condition, and so forth. The price function is partly endogenous to the facility in that it includes some variable costs,

3. See Table D-1 below, page D-10.

and partly exogenous in the form of user charges and regulation. The price function could be made to go through the point p_{mc} by the correct congestion toll, in which case the facility would be operating efficiently. Another possibility is that externalities (except delay) and agency costs are exactly offset by user charges, such that the price function follows the *AC* curve. These are special cases of the general case presented here.

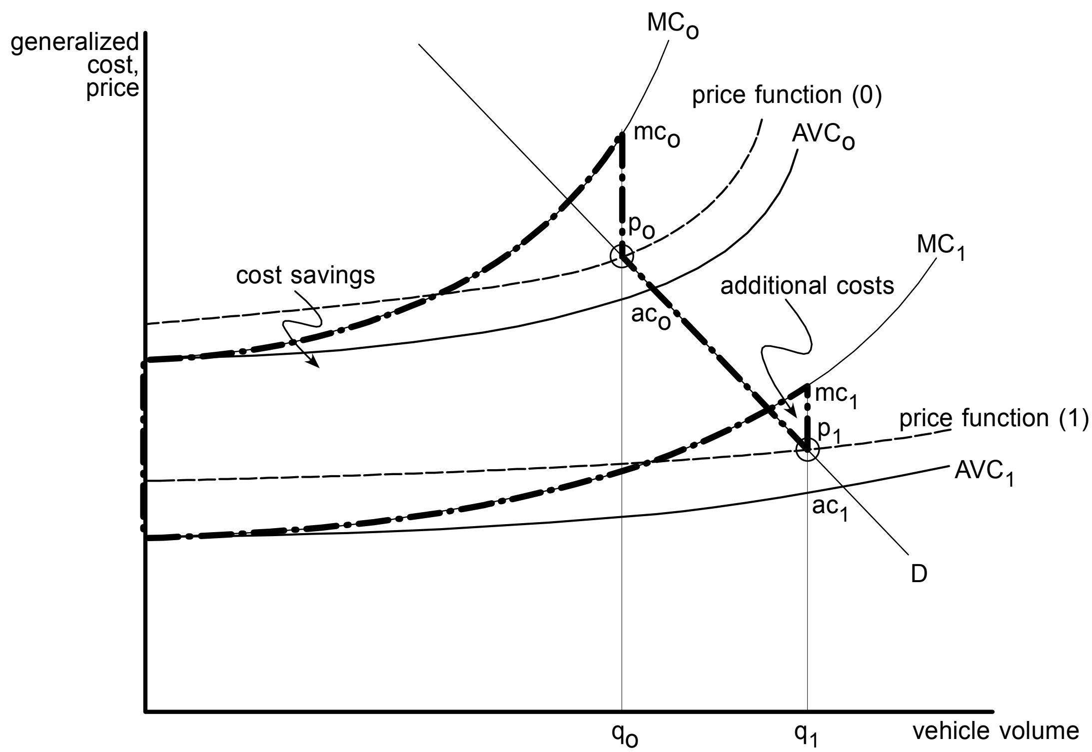

Figure D-3. Net Operating Benefit (*NOB*) for a Project.

D.2 Single-Period Evaluation

A highway improvement—resurfacing, reconstruction, additional lanes—will change user costs by some amount, resulting in operating benefits. Reductions in running costs, travel time, and accidents are both reductions in price and real benefits. Savings in agency costs and externalities are real benefits but not included in the price, whereas savings in user fees are not real benefits. The impacts of each improvement can be estimated from its induced traffic volume (based on the price and demand curve) and variable cost savings. These net operating benefits (*NOB*) are estimated for the current period, and subsequent periods, over the lifetime of the improvements. Any improvement whose *NOB* over its lifetime exceeds its capital costs is considered feasible; among feasible improvement projects, the one generating the highest net benefits is preferred.

D.2.1 Short-Run Effects of Improvements

Highway improvements that reduce congestion (by expanding capacity), or reduce vehicle wear and fuel consumption, or reduce accidents, have the effect of lowering the price to the user and stimulating greater volumes, depending upon the elasticity of demand. If the short-run price elasticity is non-zero, changes in the generalized price will cause changes in volume, within the same period, by movement along the demand curve.

To some extent, capacity expansions are self-limiting, in that induced traffic reintroduces congestion, which offsets some of the initial time savings from expansion. This supply-demand equilibrium may not result in as high a volume as would be the case if there were no congestion, but congestion will remain below the original congestion level before the capacity expansion. It is not possible for the same level of congestion to return after the expansion as before, because the short-run demand curve slopes downward to the right, and demand in the short run stays on the same demand curve. In subsequent demand periods, shifts in the demand curve might lead to higher congestion than in the current period, but such demand growth would be at least partly exogenous.[4]

D.2.2 Incremental Net Benefits

Benefits of the project are generally a combination of cost savings and additional travel. The net of such operating benefits is compared to the net or sum or fixed costs, with all values discounted or annualized as appropriate. Figure D-3 can be used to illustrate the net operating benefit (*NOB*) of the project. This diagram assumes price lies above *AVC*; the (minor) consequences of changing this assumption will be shown subsequently. The measurement of *NOB* can be defined in two ways, using different combinations of the variable cost and pricing functions and the demand curve.

D.2.3 *NOB* Based on Marginal Cost

Total variable costs for the base alternative are represented by the area under the *MC* curve up to the existing volume q_0. For the project alternative, the corresponding area is lower but extends out to q_1. The cost difference is an area of cost savings between the two curves up to q_0, and an area of additional costs under MC_1 from q_0 to q_1. The latter is offset by the (not necessarily equal) incremental benefits from the additional trips, represented by the area under the demand curve from q_0 to q_1. The resulting *NOB* is the area outlined by the dot-dash line. It can be described as the area between the two *MC* curves and under the demand curve.

Where *MC* crosses above the demand curve, the area—marked "additional costs"—is negative; these disbenefits are a consequence of underpricing the project alternative, relative to marginal cost pricing. *NOB* could be increased by this amount if the new project were efficiently priced, but this is not an option with exogenous pricing. Correspondingly, *NOB* would be smaller if it did not include the inefficiency from underpricing the base alternative.

4. This effect of exogenous growth overtaking short-run improvements is observed in TRB Special Report 245 (1995).

D.2.4 *NOB* Based on *AVC*

Because areas under the marginal cost curve can also be represented by rectangles constructed from the *AVC* curve, using the relation,

$$\int_0^q MC = q \times AVC_q \qquad \textbf{Eq. D.1}$$

the area under MC_0 up to q_0 is equal to the rectangle whose length is q_0 and whose height is ac_0 (read from AVC_0), as shown in Figure D-4. Similarly, the area under MC_1 up to q_1 is equal to the rectangle q_1 by ac_1. The difference between these two rectangles is the shaded area labeled "delay and cost savings," minus the additional costs from q_0 to q_1, plus the area under the demand curve from q_0 to q_1. This shaded area is exactly equal to the outlined area derived from the *MC* curves.

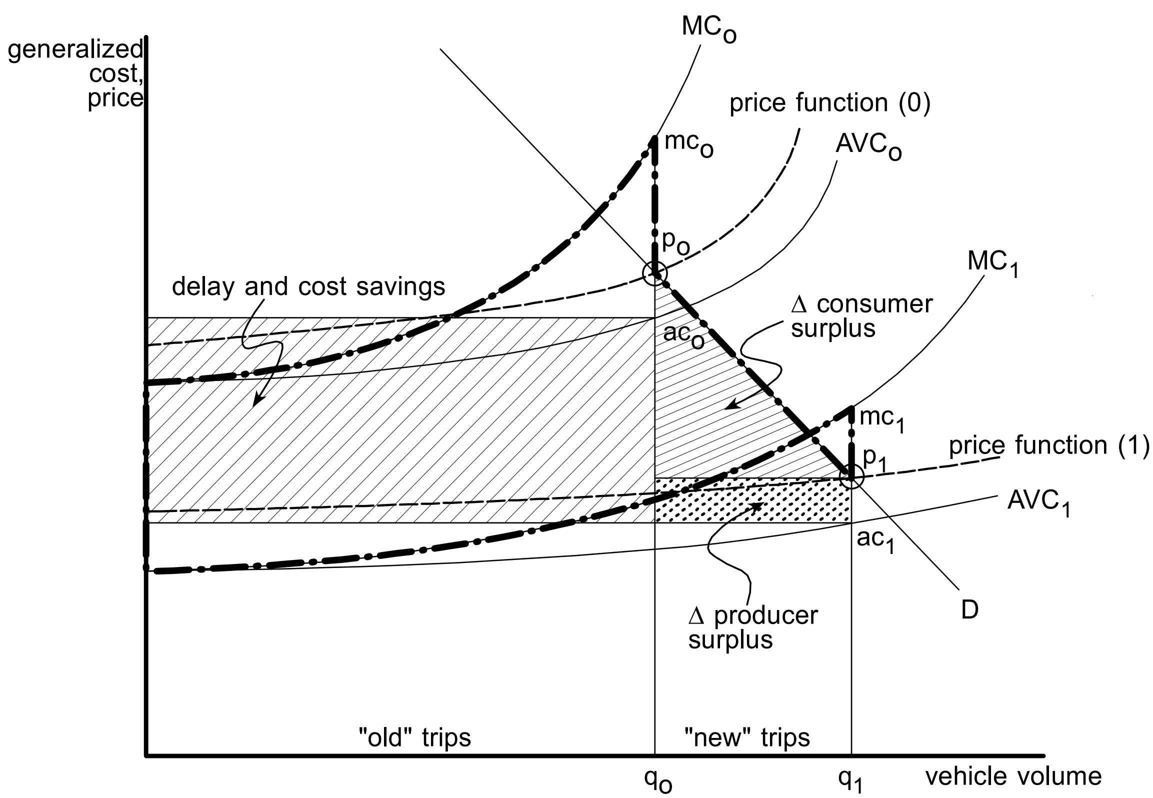

Figure D-4. *NOB* Measured from *AVC*.

D.2.5 "Old" versus "New" Trips

In practice, a distinction is made between trips that are already being made in the base case (up to q_0), or "old" trips, on the one hand, and additional trips (from q_0 up to q_1) generated by the reduction in price (from p_0 to p_1), or "new" trips, on the other.[5] A

5. It is likely, though not necessary, that most previous users of the base facility remain on the new facility to become "old" users, since they obtain what they had previously but now at a lower generalized price. The old-new distinction, however, is heuristic, rather than defining a fixed set of vehicles.

reason for making this distinction is the nature of the benefits to the two groups: old users have “demonstrated” or “revealed” (even if the demand curve is estimated or forecast) their willingness to pay for their travel, and so the benefits to them are the cost savings over their previous generalized cost. New trip makers on this facility, in contrast, have not shown any willingness-to-pay, so their benefits must be estimated from the demand curve as consumer surplus over what they actually pay when using the new project.

Although the total *NOB* areas are the same whether defined by *MC* or *AVC*, the way they partition the benefits between old and new users is not. The area under MC_1 up to q_0 indicates the total average cost if volume on the new facility were held at the volume on the base facility, but that is not what will happen; the new volume will be q_1, and costs for “old” users will be higher than if volume were held to q_0. At a volume of q_0, ac_1 would occur where AVC_1 crosses the vertical at q_0, but none of the old users actually faces this hypothetical cost on the new facility; instead they all pay the actual ac_1 at q_1. The shaded area representation based on *AVC* provides a more useful interpretation with respect to old and new users, and also allows for direct empirical estimation of the benefit components.

D.2.6 *NOB* with Price Below *AVC*

With price above *AVC*, the *NOB* diagram looks similar in shape to the first best case. This is because with price being above *AVC* there is at least a partial “toll” even if it is below marginal cost. If it is assumed that $p < AVC$, the diagram is slightly different. Figure D-5 shows such a situation, in which price is below *AVC* for both the base and project alternatives.

This diagram can be compared to Figure D-4. The outline of *NOB* based on *MC* is essentially the same, but the area defined by *AVC* curves has a somewhat different shape. Savings on old trips start above the current price, because the elimination of externalities in the base case is a benefit. Correspondingly, the benefits stop farther up, because some of the travel time and cost savings are offset by agency costs or externalities in the project alternative; cost savings would come down to p_1 were it not for the new externalities. Consumer surplus is the same in both diagrams, but a share of incremental consumer surplus in Figure D-5 is offset by additional agency costs or externalities from new trips, which might be thought of as negative producer surplus.

D.3 Components of Net Operating Benefit

Breaking *NOB* into components is useful for several reasons:

1. Most of the components can be estimated directly, whereas the *NOB* defined by MC curves can only be estimated by estimating the functional form of total variable costs.
2. Valuation can be done separately for each component, e.g., value of travel time, cost per accident.
3. The magnitudes of the components can be interpreted in meaningful terms and their relative magnitudes compared.

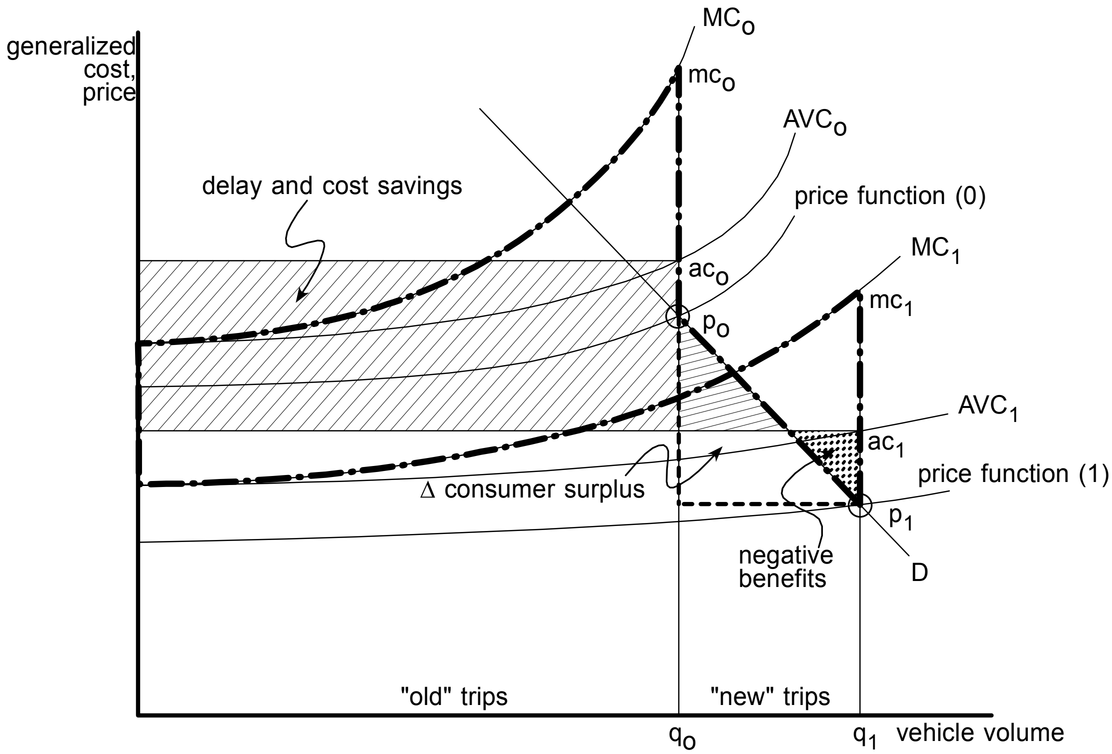

Figure D-5. *NOB* with Price Below *AVC*.

Most of the components can be disaggregated further than the major categories shown in Figures D-4 and D-5 and described below. A more detailed breakdown is provided in Table D-1. The first three columns refer to the three functions of volume previously described. Travel time is divided into normal travel time and delay, which can be anything above free-flow speed or above a v/c of, say, 0.8 of capacity. Some operating and infrastructure costs (vehicle ownership and pavement) are divided into variable and fixed as well as internal (paid by the user) and external (paid or suffered by others). Parking cost is excluded for purposes of project evaluation of highway facilities, although it may be relevant to other purposes such as price elasticities.

The fourth column notes those components included in the HERS model. Travel time and operating cost components are included in both price and cost, while infrastructure costs (agency costs) and externalities are included in cost only. HERS does not include user fees such as fuel taxes or tolls. Neither HERS nor the general theory deal with fixed user fees, such as annual fees not based on miles traveled.

Most of the major components are shown again in Figure D-6, which is similar to (and a blend of) Figures D-4 and D-5 but with the *MC* outline of *NOB* and the *MC* lines themselves omitted.

Table D-1. Price and Cost Components

	Marginal Cost	Average Cost	Price	HERS
Travel Time				
Uncongested Time	y	y	y	y
Excess Delay	MT	AD	AD	AD
Operating Cost				
Fuel	y	y	y	y
Vehicle Maintenance	y	y	y	y
Vehicle Wear	y	y	y	y
Accidents (internal)	y	y	y	y
Parking (internal)				
Vehicle Ownership				
Infrastructure				
Pavement Wear	y	y		y
Maintenance and Operation	y	y		y
Fixed Capital				
Parking (unpriced)				
Externalities				
Air Pollution	y	y		y
Water Pollution	y	y		
Noise and Vibration	y	y		
User Charges				
Tolls			y	
Excise Taxes			y	
Other Variable Fees			y	

y = cost component is included in the total for the column category
MT = marginal time cost is included
AD = average delay cost is included

D.3.1 Savings on Old Trips

Trips being taken on the base facility before the improvement and remaining on the new facility receive benefits in the form of reduced delay and operating costs. In Figure D-6, the average cost with no improvement is AVC_0 and yields an average cost of ac_0 for the base or “unimproved” volume q_0. With the improvement, ac_1 is the cost as read off the AVC_1 curve.

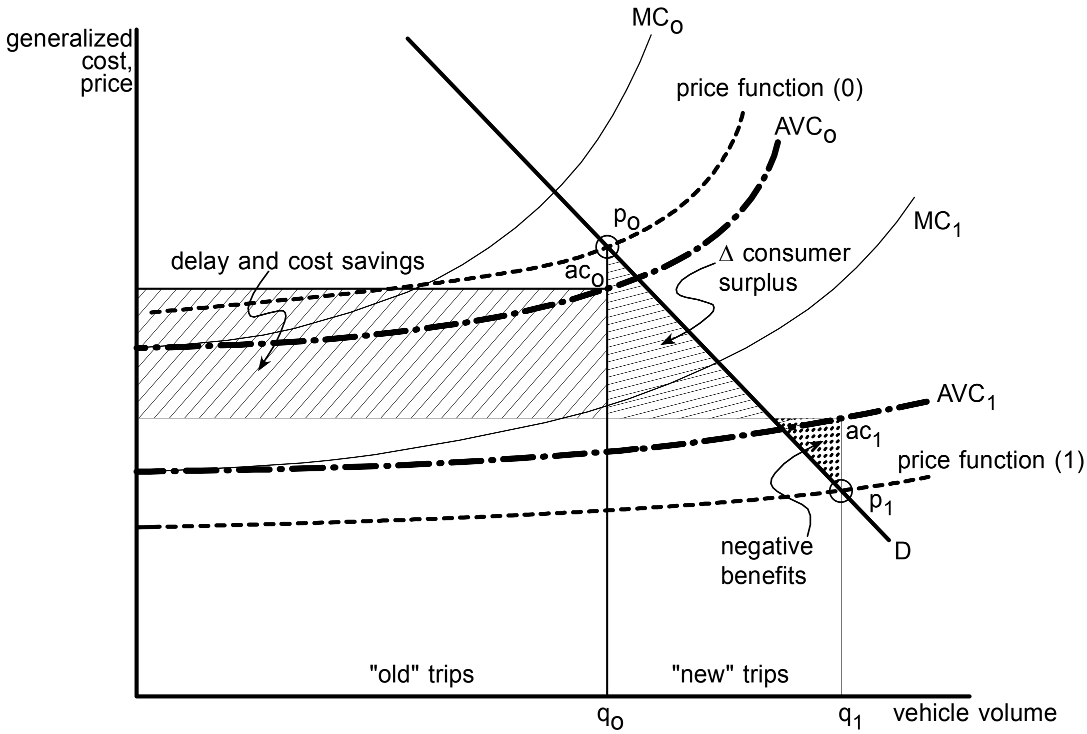

Figure D-6. Components of Net Operating Benefit (*NOB*).

Savings on old trips, then, is the difference in average cost (a_0-a_1) times the unimproved volume q_0, indicated by the shaded rectangle. All costs listed in the “Average Cost” column of Table D-1 are included. For example, fuel savings, highway maintenance cost savings, and pollution reduction are included, but fuel tax savings are ignored.

D.3.2 Incremental Consumer Surplus

Consumer surplus is the amount users would be willing to pay above what they actually pay; it is measured as an area under the demand curve between the “with” and “without” volumes, and above the price. Because incremental consumer surplus applies to induced or “new” trips, the relevant volumes in Figure D-6 are q_0 (with no improvement) and q_1 (with improvement). Data required consist of two prices and the demand curve. This consumer surplus is a triangular area whose hypotenuse is the demand curve between p_0 and p_1, and whose legs are formed by q_0 and p_1 (only the top of this triangle is shown, because the bottom is offset by external costs). Both fuel costs and fuel taxes, for example, are included in the measurement.

D.3.3 Producer Surplus on New Trips

Producer surplus is an area under the demand curve that is below what users pay but above short-run variable cost. Normally, user fees are regarded as transfers and therefore ignored in estimating benefits, but here it is simply a part of the means for valuing induced travel. Like consumer surplus, it indicates a willingness to pay for new trips. A congestion toll generates producer surplus, but only the portion on new trips is counted as a benefit; the portion applying to old trips is already counted in the time and cost savings on old trips. The net of revenues above incremental agency costs and externalities is producer surplus.

Producer surplus can be negative if payments are less than average cost. Although not comprised of revenues, users create negative externalities that are omitted from the price, so these costs can be treated symmetrically to positive producer surplus. Negative producer surplus is shown in Figures D-5 and D-6, while Figure D-4 shows positive producer surplus. In Figure D-7, the surplus of revenues over short-run cost is the rectangle with a height of (p_0-ac_0) and a length of q_0; this area is excluded from *NOB* of the project because it occurs in the base case.

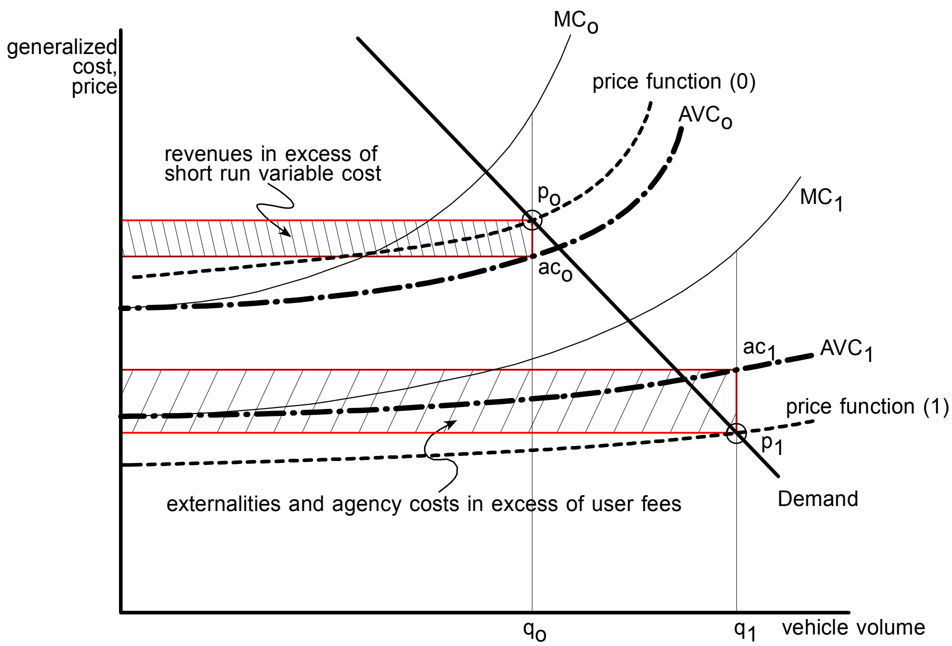

Figure D-7. Positive and Negative Producer Surplus.

D.3.4 External Costs

Negative externalities shift the marginal and average social cost curves upward, but not the price function. External costs are included in the average variable cost (*AVC*) curves in Figure D-6. Thus the *MC* and *AVC* curves in the diagram include both externality as well as time costs.

A negative externality has the opposite effect as a user charge. If the user charge and the externality happened to be equal in value (at all volume levels), then there would be no externality. In outlining the incremental *NOB* area, external costs are rectangles taken from the average cost curves, and are negative in sign. In Figure D-7, for example, the net of external and agency costs over user payments in the project alternative has a height of (ac_1-p_1) and a length of q_1. Subtracting this area from consumer surplus (for new trips) and user cost savings (on old trips) leaves the small triangle above the demand curve at the outer end in Figure D-6 as a negative benefit (i.e., traffic induced by underpricing produces costs that exceed internal benefits).

D.3.5 Externalities in Related Markets

Externalities caused by induced trips diverted from other facilities may not be adding to the total emissions of pollutants, but this is irrelevant to the present project. The only way to incorporate changes in externalities in related markets (e.g, parallel facilities) is to measure the difference in the total inefficiency with and without the improvement project; it cannot be done one item (e.g., pollution or congestion) at a time.

It seems conceptually plausible to sum up the net change in air pollution caused by a project for a region, say, and count that as the project's pollution benefit or disbenefit; then do the same for travel time, accidents, and running costs. While certainly a chore to detect the thousands of microscopic impacts occurring throughout the region, the task might be accomplished with regional simulation models.

The real problem, however, is that all of these calculations are meaningless without also calculating and summing all of the changes in consumer utility occurring at the same time, each of them the result of a shift in the demand curve in the relevant market. The likely error in such an estimate would greatly exceed the magnitude of the impact being estimated. Total air pollution in the region may be a performance measure of important policy concern, but the change in that index is not a basis for evaluating individual projects. The practical solution is to ignore what happens in related markets, except perhaps to trace out the efficiency changes for a few externalities in a few closely-related markets. The magnitude of such differences in related markets is generally small relative to benefits in the primary market.

D.4 Multi-Period Evaluation

The above steps describe a static equilibrium analysis conducted within a single short-run demand period. For each improvement alternative, the steps are repeated for each demand period over the lifetime of the improvement. Once the lifetime *NOB* is accumulated for each alternative and compared to costs, the investment choice can be made for that project.

D.4.1 Breaking the Project Life Into Discrete Demand Periods

The demand curve shifts over time in two primary patterns:

1. Periodic Daily Peaks. Demand fluctuates with time of day, typically reaching peaks in the morning and afternoon, and lows in the small hours of the night.
2. Secular Growth Trend. Average daily traffic may be growing, declining, or remaining stable over the course of years.

There are also periodic fluctuations over days of the week, and days or seasons of the year. Daily commuting peaks may be unimportant on some facilities. For evaluation, however, it is usually sufficient to recognize 1-3 daily demand period "types" and 1-4 demand periods over the investment lifetime, depending upon the rate of traffic growth.

The overall analysis period (e.g., twenty years) can be broken into shorter demand periods (e.g. 1-5 years), depending upon how rapidly exogenous demand factors are changing. Each demand period embodies a short run during which demand is assumed to be fixed, meaning that a single short-run demand curve applies for the duration of the period. This "single" demand can still be composed of several periodic demand curves, such as peak and off-peak, or it could be a daily average.

Once the overall analysis period is broken into demand periods, the secular or trend forecast becomes a series of discrete points representing the midpoints of demand periods. These points provide the origins or calibration points for the associated short-run demand curves.

D.4.2 Growth in Demand

Even in the short run, demand stimulated by reduction in the generalized price generates enough traffic to partly offset the gains from increased capacity. In the long run, this effect can be exaggerated, when general growth in demand and highway improvements reinforce each other to increase traffic volumes. A casual observer of this process can easily come to the conclusion that building more road capacity is self-defeating, because congestion is soon back to where it was. For those trying to carry out benefit-cost analysis, the benefits seem to disappear. The reality, however, is a bit different.

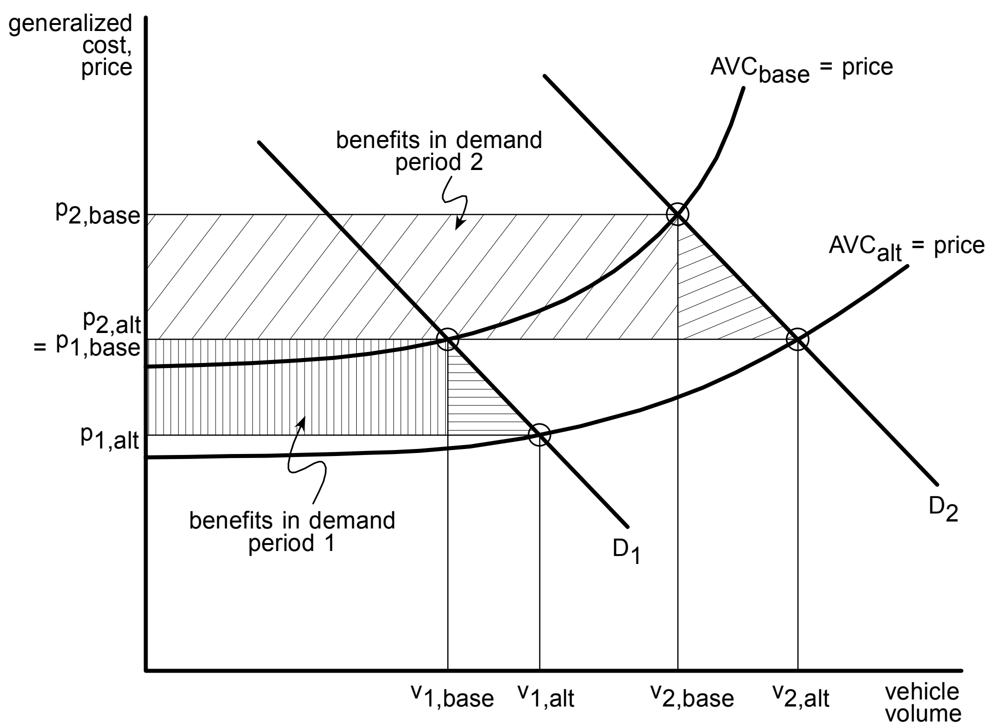

Figure D-8. Benefits From a Project in Two Demand Periods.

The simplest case is shown in Figure D-8, in which a base alternative and a project alternative are represented by their *AVC* curves, and these also give the price to the user under each alternative. Two demand curves are included, D_1 for the first period of time and D_2 for the next period. The curves are drawn such that, by coincidence, the cost to the user in the first demand period under the no-build alternative is the same as the price in the second period under the project alternative. In other words, users are individually no better off after the improvement than before.

This does not mean, however, that there are no benefits. First, there is more travel than was the case under the base alternative. Second, the relevant comparison is not to the price and volume in period one, but to the period two base case—i.e., the conditions that would have occurred in period two if the improvement had not been made. With an exogenous growth in demand, congestion would have been much worse without the improvement, and less travel would have been served. Hence, there is positive incremental *NOB* in the first period, and additional (and larger) *NOB* in the second demand period. Together (assuming only two periods) these account for project benefits, to be compared against incremental capital costs.

A more general case is illustrated in Figure D-9, in which user price does not follow the average cost curve. In this case, price is above average cost (compare this to Fig-

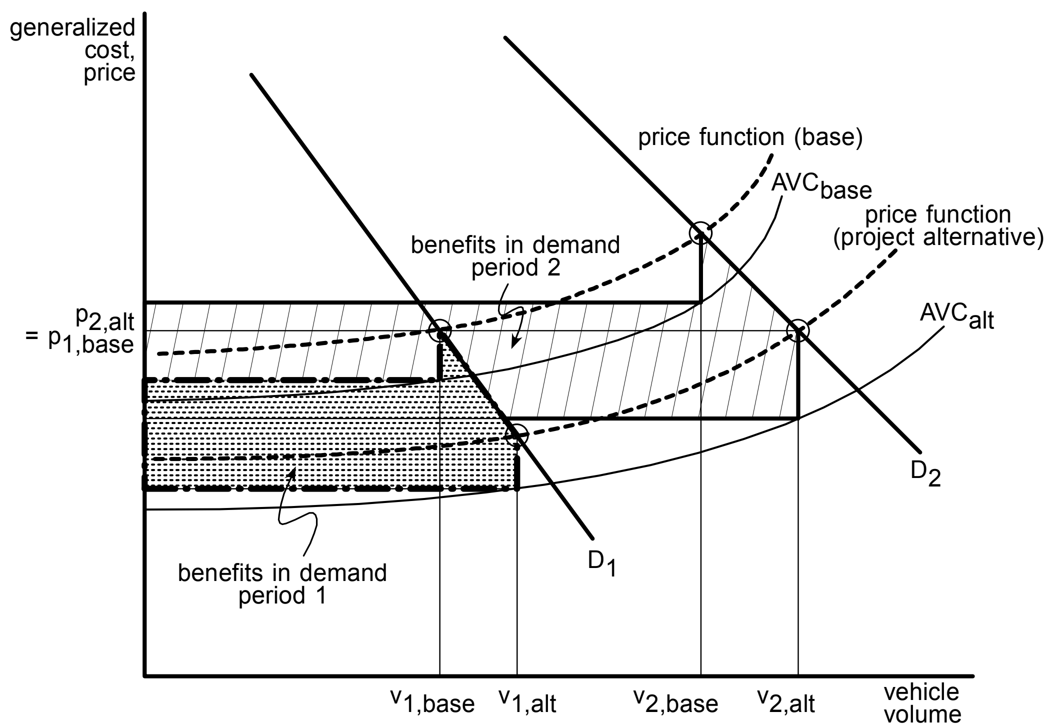

Figure D-9. *NOB* For Two Demand Periods with Pricing Above *AVC*.

ure D-4, the single-period case with price above *AVC*). The MC curve is omitted because pricing inefficiency is ignored, i.e., a second-best investment comparison is assumed. Price is again arbitrarily set so as to equate base alternative price in the first period to the price with the improvement in the second period. Again, the areas of *NOB* are outlined and shaded, and together form the *NOB* for the project alternative.

Because price is above AVC for the project alternative, *NOB* includes some producer surplus on new trips, in addition to consumers surplus.

A final configuration, shown in Figure D-10 illustrates the case when price is below social cost for both alternatives. The two demand periods are independent of each other. Each of these periods is similar to Figure D-5.

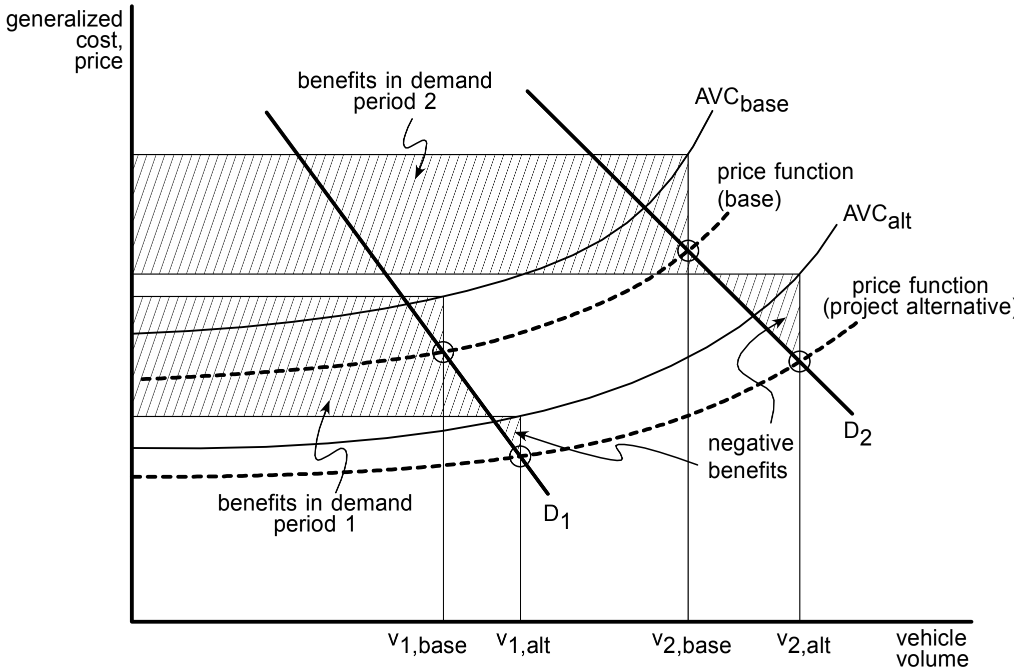

Figure D-10. *NOB* for Two Demand Periods with Price Below *AVC*.

In summary, each demand period is handled as a single period, in which the short-run demand curve is fixed to a point based on the actual or forecast traffic at an associated price. Within the demand period, volume can move along the demand curve depending upon reductions in generalized price resulting from improvements being evaluated. Between demand periods, demand can shift and facilities wear out, resulting in a new set of cost and demand curves. The sum of the discounted benefits in each demand period is the present value of project benefits. This is true whether pricing is efficient at $p = MC$, price follows *AC*, or pricing follows neither of the above.

The HERS model produces results like those shown in Figure D-10 because agency costs and air pollution (if the module is enabled) are included. If other negative externalities (e.g., noise, water pollution, external costs of accidents) were modeled in HERS, the gap between average variable cost and the price function would be wider. The model cannot produce results of the type shown in Figure D-9 because there is no price in the model that is separate from other user costs.

D.5 Summary

1. Three functions (or selected points along them) are needed to define the base and project alternatives for evaluation: marginal cost, average cost, and price, as enumerated in Table D-1.
2. For benefit-cost analysis, changes in costs determine incremental benefits, whereas changes in the generalized price lead to induced travel.
3. Incremental net operating benefit (*NOB*) of a project alternative relative to the base alternative can be defined using marginal or average cost curves, but the latter is ultimately more practical.
4. The primary components of *NOB* are delay and cost savings on old trips, consumer surplus on new trips, and producer surplus on new trips. The latter may be negative if agency costs and environmental externalities exceed user payments.
5. Each demand period is a single evaluation of *NOB*. Demand periods can be periodic, such as peak and off-peak, as well as discrete intervals on a secular growth trend.
6. Changes in user costs (time, running costs, accidents, user charges) cause changes in traffic volumes, referred to as induced traffic or induced demand. These effects should be incorporated into benefit-cost evaluation of improvement projects.
7. Multiple demand periods (periodic and secular) are discounted and accumulated for comparison to fixed costs to assess the net benefits of an improvement project.

These concepts are readily made operational, and can be implemented in spreadsheet or other models.

D.6 A Numerical Example

Table D-2 shows some hypothetical data for a single demand period for one project alternative versus the base case. All of the data are converted from whatever natural units (e.g., minutes, crashes, grams) they might have been generated in to dollars per vehicle trip over the facility. All of the bolded numbers are required input data about costs and pricing that must be estimated for the specific conditions of the project, including the volumes that will occur at the relevant prices. Capacities of the existing and expanded facilities are also required.

Calculations are done on the basis of two contrasting assumptions:

1. First-best pricing and investment, assuming that price can be set so as to maximize net benefits of both operation and investment. Numerical values for prices and volumes, and the outlines for *NOB*, are shown in Figure D-11.
2. Second-best pricing, assuming that user fees are determined exogenously and cannot be changed. Prices and volumes are shown in Figure D-12, which is similar to Figure D-5.

Total *NOB* as well as the major components under each of the two assumptions are shown in Table D-3. Areas in the diagrams correspond to components of *NOB* in the

Table D-2. Input Data for Example Project Evaluation

$ per trip	BASE	PROJECT	Marginal Cost	Price	Average Cost
RUNNING COSTS	**2.80**	**1.75**	1	1	1
Vehicle Wear	0.90	0.60			
Fuel	0.80	0.55			
Maintenance	0.50	0.30			
Insurance/Accidents	0.60	0.30			
Parking (internal)	0.00	0.00			
Other	0.00	0.00			
HIGHWAY COSTS	**0.50**	**0.40**	1		1
Pavement Wear	0.30	0.30			
Administration	0.20	0.10			
Parking (unpriced)	0.00	0.00			
Other	0.00	0.00			
USER CHARGES	0.15	0.15		1	
EXTERNALITIES	**1.10**	**1.10**	1		1
Pollution	0.50	0.60			
Noise	0.40	0.40			
Accidents (external)	0.20	0.10			
Other	0.00	0.00			
TRAVEL TIME COST	6.80	3.40			
Free Flow	**1.80**	**1.40**	1	1	1
Excess Delay	**5.00**	**2.00**		1	1
MARGINAL COST	6.20	4.65	<----		
PRICE	9.75	5.30		<----	
AVERAGE COST	11.20	6.65			<----
efficient price	12.19	7.31			
efficient toll	5.99	2.66			
efficient volume	4,000	6,000			
OTHER DATA AND PARAMETERS					
Capacity (veh/hr)	**4,000**	**6,000**			
Volume (act/est)	**5,000**	**6,826**			
elasticity	**-0.80**				

table. For example, savings on old trips in the first-best evaluation are measured by the rectangle

$$SOT = (6.20 \angle 4.65) \times 4000 = 6{,}200 \quad \textbf{\textit{Eq. D.2}}$$

which is composed of normal running time savings = (1.80-1.40) *x* 4000 = 1,600, plus running cost savings = $(2.80 \angle 1.75) \times 4,000 = 4,200$, plus delay savings = zero with efficient pricing, plus highway operating cost savings $(0.50 \angle 0.40) \times 4,000 = 400$.

Numbers for the "Existing" facility show the net benefits of operating the facility efficiently (i.e., correctly priced) or inefficiently, and do not enter into the benefit-cost evaluation of the expansion project.

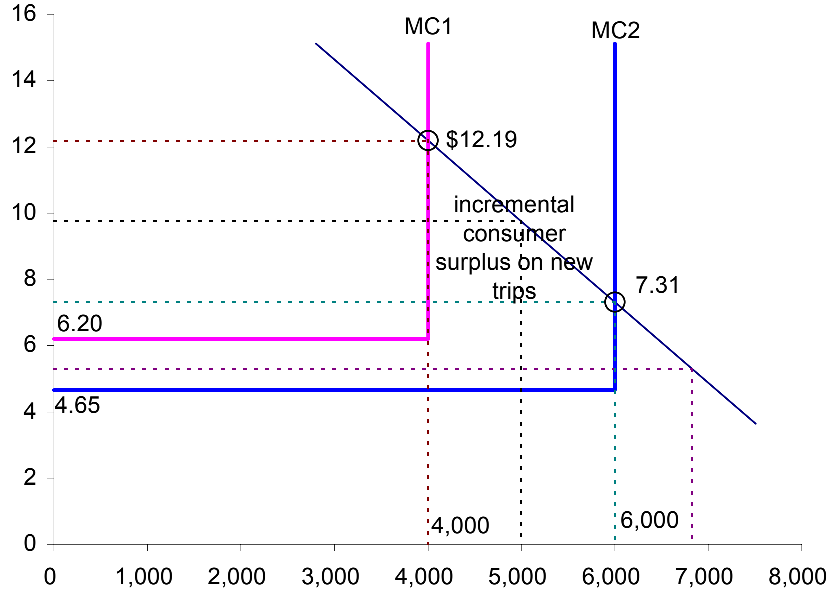

Figure D-11. First-best Net Operating Benefit (*NOB*).

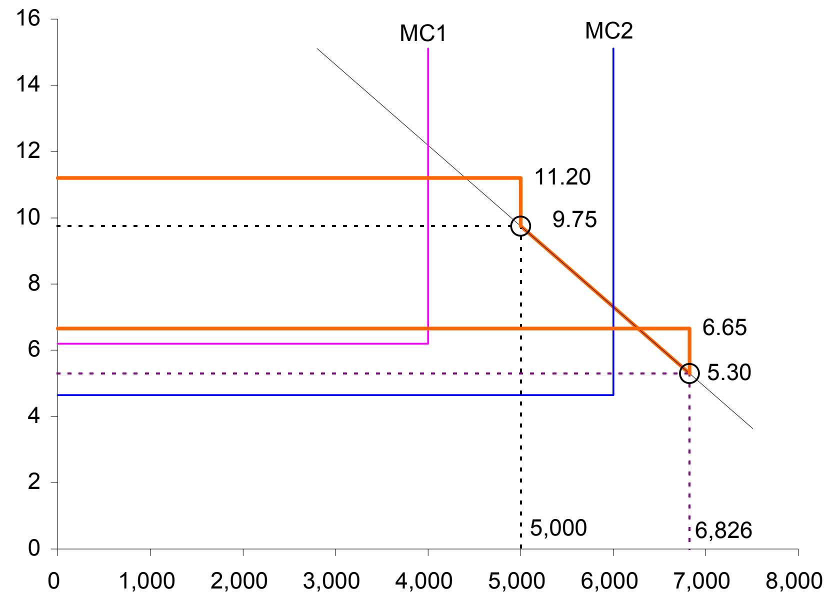

Figure D-12. Second-best Net Operating Benefit (*NOB*).

Table D-3. First-Best and Second-Best *NOB* for the Example Project

	Existing		Expansion	
NET OPERATING BENEFITS	efficient	inefficient	1stB	2ndB
normal running time savings on old trips			1,600	2,000
running cost savings on old trips			4,200	5,250
delay savings on old trips				15,000
externality cost savings on old trips			0	0
highway operating cost savings on old trips			400	500
incremental consumer surplus on new trips	19,500	30,469	4,875	4,062
producer surplus on new trips	23,950	750	5,325	274
externality costs on new trips		(5,500)		(2,008)
highway operating costs on new trips		(2,500)		(730)
Total NOB	43,450	23,219	16,400	24,347

D.7 References

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Appendix E:

Operating Cost Equations

Vehicle operating cost equations are disaggregated by vehicle type (small auto, medium/large auto, 4-tire trucks, 6-tire trucks, 3+ axle single-unit trucks, 3-4 axle combination trucks, and 5+ axle combination trucks) and by cost component (fuel, oil, tires, maintenance, and depreciation), under constant speed conditions. Also, additional operating costs due to speed variability are provided for all seven vehicle types and all five cost components, and additional operating costs due to horizontal curvature are provided for all seven vehicle types for three of the cost components (fuel, tire wear, and maintenance). Finally, a set of pavement condition adjustment factors to constant-speed operating costs are generated for each of the five cost components (fuel and oil are combined in one equation) as functions of pavement surface quality (PSR).

E.1 Sources of HERS Operating Cost Equations

The computations for the operating cost components in HERS are based on the report "*Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors"*, by J.P. Zaniewski, et.al., Texas Research and Development Foundation, June 1982. This report was prepared for the U. S. Department of Transportation, Federal Highways Administration.

In the Zaniewski report, operating costs are listed in tables in Appendix B. There are three categories of tables matching the HERS categories: constant-speed operating costs; excess cost due to speed change cycles; and excess costs due to horizontal curvature. The Zaniewski tables for constant-speed operating costs are given as a matrix of speed in miles per hour and gradient. The miles per hour are given from 5 to 70 in increments of 5-m.p.h. The gradient is given from -8% to 8% in increments of 1%.

The tables for excess cost due to horizontal curvature are organized as a matrix of degrees of curvature (1°, 2°... 6°, 8°, 10°... 20°, 25°, 30°) and speed in miles per hour (5 to 70 in 5-m.p.h. increments).

The Zaniewski data were scanned and converted to spreadsheet form. Some corrections were applied where it appeared that the original data were misleading.

In two cases, data from the Zaniewski report demonstrated constant-speed fuel consumption of 0.0 over a broad range of gradient and speed. In these cases, data from alternate sources were used in place of the Zaniewski data. These sources were P. J. Claffey and Associates, "Running Costs of Motor Vehicles as Affected by Road Design and Traffic," *NCHRP Report* 111, Highway Research Board, National Research Council, Division of Engineering, 1971; and Daniels, C. *Vehicle Operating*

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E.1.1 Region of Interest

For constant-speed operating costs, the data between gradients of -3% and 3% (inclusive) are considered important. Speeds of up to 90 miles per hour are also important, and are extrapolated from existing data. Data for speeds of 2 miles per hour are also extrapolated.

For excess cost due to curvature, only speed/curvature settings below the value of *VCURVE* (Equation 5.39) are considered important. In some cases, at a low degree of curvature, data must be extrapolated to 90-m.p.h.

E.1.2 Updating of Operating Cost Equations

An analysis of the operating cost equations of the December 2000 version of HERS revealed discontinuities within some of the equations. As a result, many of the operating cost equations have been revised to provide better accuracy and to eliminate the discontinuities within the constant-speed operating cost equations. The equations for excess cost due to curvature were updated as well to establish complete coverage of the equations, thus eliminating the practice of interpolating values obtained from a look-up table.

Table E-1 displays the complete array of operating cost equations, and indicates which constant-speed and excess cost due to curvature equations were updated.

E.1.2.1 Determining Which Equations Required Updating

Existing constant-speed operating costs equations were examined graphically within the region of interest (-3% to 3% gradient, 2–90 m.p.h.) to look for discontinuity or other forms of error (e.g. values less than 0; arcing towards infinity, especially in the extremes). The results were also compared, graphically, to the source data. If the results show a noticeable discontinuity or a poor resemblance to the source data, then the equations for that component were updated. The graphical examination used gradient increments of 0.25% between the range of -3% to 3%, and increments of 1-m.p.h. between 2- and 90-m.p.h. Gradient ranges of between -8% to -3% and 3% to 8% were also examined for erratic behavior, though this examination was not as exacting as within the region of interest.

In the case of excess operating costs due to curvature, the previously equations applied to cases of speeds of greater than or equal to 55-m.p.h. New equations were generated for the complete region of interest.

E.1.2.2 Method and Tools Employed

Microsoft Excel was used for graphic display of the data to examine for discontinuity and to compare, graphically, against the original data. Curves were also segmented or re-segmented in spreadsheets (different equations may be used for different portions of the speed or gradient, and segmentation may have been increased or, more often, simplified).

Data from the spreadsheets were then read by a software package called ‘TableCurve 3D’, by SPSS. TableCurve produces a list of equations to predict the output based on the two input variables (gradient and speed). The equations are ranked by adjusted r^2 score. The first pass attempts to find a reasonable fit with a maximum of five terms. If

Table E-1. Equation Update Summary

Component	Vehicle Type						
	Small Auto	Med/ Large Auto	4-Tire Truck	6-Tire Truck	3+ Axle Single -Unit Truck	3-4 Axle Combo Unit Truck	5+ Axle Combo Unit Truck
Constant-Speed Fuel Consumption	♦	♦	♦	♦	♦	♦	♦
Constant-Speed Oil Consumption	♦	♦		♦			
Constant-Speed Tire Wear			♦			♦	
Constant-Speed Maintenance and Repair				♦	♦	♦	
Constant-Speed Depreciation							
Speed Variability Fuel Consumption							
Speed Variability Oil Consumption							
Speed Variability Tire Wear							
Speed Variability Maintenance and Repair							
Speed Variability Depreciation							
Curvature Fuel Consumption	♦	♦	♦	♦	♦	♦	♦
Curvature Tire Wear	♦	♦	♦	♦	♦	♦	♦
Curvature Maintenance and Repair	♦	♦	♦	♦	♦	♦	♦

♦ = equation updated

a good fit is not found, then the term count is stepped until either a reasonable fit is found or that it becomes apparent that resegmenting is necessary. Final equations were tested for continuity and conformity to the original data.

E.1.2.3 Notable Exception: 3-4 Axle Combination Unit Trucks

For reasons noted above, the data from the Zaniewski report were not used directly for constant-speed fuel consumption (CSFC) for 3-4 axle combination unit trucks and 5+ axle combination unit trucks. Data from the Claffey study, adjusted to scale, were used for 3-4 axle CU trucks. It should be noted that the Zaniewski data are consistent with the Claffey data at steep uphill gradients ($GR \geq 3$) across the range of speed, and at lesser gradients up to 30 m.p.h.

E.1.2.4 Notable Exception: 5+ Axle Combination Unit Trucks

The Zaniewski report states that the data for 3-S2 semi (5+ axle CU) trucks were extrapolated from 2-S2 semi (3+ axle CU) trucks, yet the report does not state the method applied for this extrapolation. For the HERS equations, the following method was applied to obtain constant-speed fuel consumption equations for 5+ axle CU trucks:

- The percentage difference of fuel consumption rates from 2-S2 semi (3-4 Axle CU truck) and 3-S2 semi (5+ axle CU truck) from the Zaniewski report was derived for all gradient/speed points.
- The average percentage difference for each gradient was then generated. For gradients less than(-1), where the data becomes zero for both vehicle types, the percentage difference from gradient of (-1) is used. This created an asymptote

on the consumption curve as the gradient gets steeper downhill, consistent with both the Claffey and Daniels findings.

- The 3-4 axle CU truck CSFC data (generated from Claffey) were incremented by the average percentage differences, along gradients, from the Zaniewski report, to create CSFC data points for 5+ axle CU trucks.

The new data tables for both 3-4 Axle CU trucks and 5+ axle CU trucks were then rendered using Microsoft Excel and processed using TableCurve, as shown above.

E.2 The Operating Cost Equations

The equations below are grouped by vehicle type, then by component. Equations are typically segmented, and the conditions to define the range of the segments are given along with the equation for that segment. The tables are presented in the following order:

- Small Auto (Tables E-2 through E-14)
- Medium/Large Auto (Tables E-15 through E-27)
- 4-Tire Truck (Tables E-28 through E-40)
- 6-Tire Truck (Tables E-41 through E-53)
- 3+ Axle Single-Unit Truck (Tables E-54 through E-66)
- 3-4 Axle Combination Truck (Tables E-67 through E-79)
- 5+ Axle Combination Truck (Tables E-80 through E-92)
- Pavement Adjustment Factors (Tables E-93 through E-96)

Within each vehicle type, equations are presented in the order shown in Table E-1.

The list below gives the variable names used in the equations:

AES	=	average effective speed
GR	=	grade (in percent)
CSMAX	=	maximum speed during speed change cycle
DCA	=	degrees of curvature
CSFC	=	constant-speed fuel consumption (gallons/1000 miles)
CSOC	=	constant-speed oil consumption (quarts/1000 miles)
CSTW	=	constant-speed tire wear (% worn/1000 miles)
CSMR	=	constant-speed maintenance and repair (% avg. cost/1000 miles)
CSVD	=	constant-speed depreciation (% new price/1000 miles)
PCAFOC	=	pavement condition adjustment factor for oil consumption
PCAFTW	=	pavement condition adjustment factor for tire wear

PCAFMR	=	pavement condition adjustment factor for maintenance and repair
PCAFVD	=	pavement condition adjustment factor for depreciation expenses
SCCFC	=	excess fuel consumption for speed change cycles (gallons/1000 cycles)
SCCOC	=	excess oil consumption for speed change cycles (quarts/1000 cycles)
SCCTW	=	excess tire wear for speed change cycles (% worn/1000 cycles)
SCCMR	=	excess maintenance and repair for speed change cycles (% average cost/1000 cycles)
SCCD	=	excess depreciation for speed change cycles (% new price/1000 cycles)
CFC	=	excess fuel consumption due to curves (gallons/ 1000 vehicle miles)
CTW	=	excess tire wear due to curves (% worn/1000 vehicle miles)
CMR	=	excess maintenance and repair due to curves (% average cost/1000 vehicle miles)
PSR	=	pavement serviceability rating

E.3 Small Automobile

E.3.1 Constant-Speed Fuel Consumption (CSFC)

Table E-2. Small Automobile Constant-Speed Fuel Consumption

1	**Condition**	$GR \geq 0$
	Equation	$CSFC = 100.82 - 4.9713*AES + 0.11148*AES^2 - 0.0011161*AES^3 + 5.1089e\text{-}06*AES^4 + 3.0947*GR$
2	**Condition**	$GR < 0$ and $AES \leq 40$
	Equation	$CSFC = (91.045 - 4.0552*AES + 0.060972*AES^2 + 4.0504*GR + 0.4227*GR^2) / (1 - 0.014068*AES + 0.0004774*AES^2 - 0.045957*GR + 0.0054245*GR^2)$
3	**Condition**	$GR < 0$ and $AES > 40$
	Equation	$CSFC = 23.373 + 3.6374*GR + 0.21681*GR^2 + (72.562 / (1 + \exp(-((AES - 81.639) / 7.4605))))$

E.3.2 Constant-Speed Oil Consumption (CSOC)

Table E-3. Small Automobile Constant-Speed Oil Consumption

1	**Condition**	GR > 0 and AES < 55
	Equation	$CSOC = \exp(2.7835 - 0.79034*\ln(AES) - 1.1346 / (AES^{(1.5)}) + 0.65342*(GR^{(0.5)}))$
2	**Condition**	GR ≥ 0 and 55 ≤ AES < 70
	Equation	CSOC = -170.4 + 34.02*ln(AES) + 1939/AES + 0.4747*GR - 0.003296*AES*GR
3	**Condition**	GR ≥ 0 and AES ≥ 70
	Equation	CSOC = -170.4 + 34.02*ln(AES) + 1939/AES+0.27*GR
4	**Condition**	GR ≤ 0 and AES < 55
	Equation	$CSOC = 1.0435 + (327.89/((1 + (((AES + 7.1977)/3.0141)^2)) * (1 + (((GR + 8.0484)/2.8984)^2))))$
5	**Condition**	Otherwise
	Equation	CSOC = -170.4+34.02*ln(AES)+1939/AES

E.3.3 Constant-Speed Tire Wear (CSTW)

Table E-4. Small Automobile Constant-Speed Tire Wear

1	**Condition**	GR ≥ 2.5 and AES < 55
	Equation	$CSTW=\exp(-2.55+0.0001621*AES^2+0.01441*AES+1.473*\ln(GR)-0.001638*AES*GR)$
2	**Condition**	GR ≥ 2.5 and AES ≥ 55
	Equation	$CSTW=1.314+0.000733*AES^2-0.05758*AES+0.01514*GR^2 +0.003997*AES*GR$
3	**Condition**	(0 < GR < 2.5 and AES < 15) or (-AES/20 < GR < 2.5 and AES ≥ 15)
	Equation	$CSTW=0.1959+2.51*10^{-6}*AES^3-0.0352*\ln(AES)+0.01754*GR^2+0.00348*AES*GR$
4	**Condition**	(-1.5 < GR ≤ 0 and AES < 15) or (-AES/10 < GR ≤ -AES/20 and AES ≥ 15)
	Equation	$CSTW=0.0604+2.92*10^{-8}*AES^4+0.0000796*AES^2+0.0274*GR^2+0.074*GR+ 0.0000568*AES^2*GR$
5	**Condition**	otherwise
	Equation	$CSTW=\exp(-5.39-0.000895*AES^2+0.0962*GR+2.83*\ln(-GR)-0.00397*AES*GR)$

E.3.4 Constant-Speed Maintenance and Repair (CSMR)

Table E-5. Small Automobile Constant-Speed Maintenance and Repair

1	**Condition**	GR ≥ 0
	Equation	$CSMR=48.3+0.00865*AES^2+0.0516*AES*GR$
2	**Condition**	(-1.5 ≤ GR < 0 and AES ≤ 25) or (GR < 0 and 25 < AES < 55 and AES ≥ -12.2*GR+4)
	Equation	$CSMR=45.1+0.00582*AES^2+0.23*AES+0.0502*AES*GR$
3	**Condition**	(GR < -1.5 and AES ≤ 25) or (GR < 0 and 25 < AES < 55 and AES < -12.2*GR+4)
	Equation	$CSMR = -5.83-0.01932*AES^2-23.4*GR$
4	**Condition**	-0.14*AES+3.6 < GR < 0 and AES ≥ 55
	Equation	$CSMR=73.35+0.01397*AES^2-0.7398*AES+0.04994*AES*GR$
5	**Condition**	otherwise
	Equation	$CSMR=4.27-0.0208*AES^2-23.63*GR$

E.3.5 Constant-Speed Depreciation (CSVD)

Table E-6. Small Automobile Constant-Speed Vehicle Depreciation

1	**Condition**	all
	Equation	CSVD = 2.2+0.001596*AES-0.38*ln(AES)

E.3.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-7. Small Automobile Excess Fuel Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCFC=0.00424*CSMAX^3$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCFC=0.04547+0.08559*CSMAX+3677*10^{-8}*CSMAX^3$

E.3.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-8. Small Automobile Excess Oil Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCOC=0.00004*CSMAX^3$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCOC=0.000879+0.000934*CSMAX-1612*10^{-8}*CSMAX^2+193*10^{-9}*CSMAX^3$

E.3.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-9. Small Automobile Excess Tire Wear Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCTW=0.0008*CSMAX^{2}$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCTW=\exp(-7.112+1.999*\ln(CSMAX)- 8384*10^{-8}*CSMAX^{2})$

E.3.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-10. Small Automobile Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCMR=0.0016*CSMAX^{2}$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCMR=\exp(-6.284+0.006889*CSMAX+1.881*\ln(CSMAX) - 7388*10^{-8} *CSMAX^{2})$

E.3.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-11. Small Automobile Excess Depreciation Due to Speed Variability

1	**Condition**	CSMAX < 60
	Equation	SCCD=0.0004*CSMAX
2	**Condition**	$CSMAX \geq 60$
	Equation	$SCCD=\exp(-4.327+0.000168*CSMAX^{2})$

E.3.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-12. Small Automobile Excess Fuel Consumption Due to Curves

1	**Condition**	AES ≥ (1/(0.001147 + 0.008062*DCA$^{(0.5)}$ + 0.008862/DCA))
	Equation	CFC = MAX(0, 18387.7115*(1 / (1 + (DCA/39.459)$^{(-3.0419)}$))* 1 / (1 + (AES/104.38)$^{(-6.2768)}$))
2	**Condition**	DCA ≥ 6 and AES > 10 and AES ≤ (-0.6807*DCA + 30.944)
	Equation	CFC = MAX(0, -0.046905 + 0.95904*LN(DCA) - 0.02218*AES - 0.17662*(LN(DCA))^2 + 0.000957*AES^2 - 0.021388*AES*LN(DCA))
3	**Condition**	(DCA ≥ 6 and AES ≤ 10) or (DCA < 6 and AES ≤ 25)
	Equation	CFC = MAX(0, -1.9503 + 1.0112*LN(DCA) + 0.31328*AES - 0.16763*(LN(DCA))^2 - 0.012903*AES^2 - 0.031507*AES*LN(DCA))
4	**Condition**	Otherwise
	Equation	CFC = 0

E.3.12 Excess Tire Wear Due to Curves (CTW)

Table E-13. Small Automobile Excess Tire Wear Due to Curves

1	**Condition**	(DCA≥16 and AES ≥ (-0.031746*DCA^2 + 0.74603*DCA + 21.19)) or (16 > DCA ≥ 6 and AES ≥ (45 - 1.9167*DCA + 0.041667*DCA^2)) or (DCA < 6 and AES ≥ (-442.3 + 2959.4/DCA$^{(0.5)}$ - 6735.1/DCA + 6810.6/DCA$^{(1.5)}$ - 2582.5/DCA^2))
	Equation	CTW = MAX(0, 351887 * EXP(-EXP(-(DCA - 51.408)/19.756) - (DCA-51.408)/19.756 + 1) * EXP(-EXP(-(AES - 122.22)/38.201) - (AES-122.22)/38.201 + 1))
2	**Condition**	(DCA ≥ 16 and AES < (-0.031746*DCA^2 +0.74603*DCA + 21.19)) or (16 > DCA ≥ 8 and AES < (45 - 1.9167*DCA + 0.041667*DCA^2))
	Equation	CTW = MAX(0, -21.508 + 13.474*LN(DCA) + 19.67*LN(AES) - 1.5206*(LN(DCA))^2 - 3.5315*(LN(AES))^2 - 3.6298*LN(DCA)*LN(AES))
3	**Condition**	(8 > DCA ≥ 6 and AES < (45 - 1.9167*DCA + 0.041667*DCA^2)) or (DCA < 6 and AES < (-442.3 + 2959.4/DCA$^{(0.5)}$ - 6735.1/DCA + 6810.6/DCA$^{(1.5)}$ - 2582.5/DCA^2)
	Equation	CTW = MAX(0, -3.3578 + 3.5095*DCA + 0.080638*AES - 0.18665*DCA^2 - 0.00054297*AES^2 - 0.061173*DCA*AES)

E.3.13 Excess Maintenance and Repair Due to Curves

Table E-14. Small Automobile Excess Maintenance and Repair Due to Curves

1	**Condition**	(DCA > 10 and AES ≥ -0.65*DCA + 34.5) or (DCA < 10 and AES ≥ -2.4444*DCA + 52.444)
	Equation	$CMR = MAX(0, EXP(-19.624 - 1.0614*DCA^{(0.5)}*LN(DCA) + 6.4853*DCA^{(0.5)} + 0.033374*AES^{(1.5)} - 0.00046284*AES^{2}*LN(AES)))$
2	**Condition**	5 ≤ DCA ≤ 10 and (-1*DCA + 20) ≤ AES ≤ (-1*DCA + 25)
	Equation	CMR = 0.1
3	**Condition**	Otherwise
	Equation	CMR = 0

E.4 Medium/Large Automobile

E.4.1 Constant-Speed Fuel Consumption (CSFC)

Table E-15. Medium/Large Automobile Constant-Speed Fuel Consumption

1	**Condition**	AES ≤ 40
	Equation	$CSFC = 88.556 - 3.384*AES + 1.7375*GR + 0.053161*AES^{2} + 0.18052*GR^{2} + 0.076354*AES*GR$
2	**Condition**	AES > 40
	Equation	$CSFC = 85.255 - 2.2399*AES + 2.7478*GR + 0.028615*AES^{2} + 0.041389*GR^{2} + 0.046242*AES*GR$

E.4.2 Constant-Speed Oil Consumption (CSOC)

Table E-16. Medium/Large Automobile Constant-Speed Oil Consumption

1	**Condition**	GR > 0 and AES < 55
	Equation	$CSOC = exp(-1.5698 + 9.8768/AES^{(0.5)} - 7.6187 /AES + 0.70702*GR^{(0.5)})$
2	**Condition**	GR ≥ 0 and 55 ≤ AES < 70
	Equation	$CSOC = 9.5234-0.29873*AES +0.0026913*AES^2 + 0.28997*GR^{1.00129}$
3	**Condition**	GR ≥ 0 and AES ≥ 70
	Equation	CSOC = -173.3 + 34.6*ln(AES) + 1973/AES + 0.29*GR
4	**Condition**	-3 ≤ GR ≤ 0 and 15 ≤ AES < 55
	Equation	$CSOC = 0.42295 + 0.35839*AES - 0.029984*AES^2 + 0.0010392*AES^3 - 0.000016196*AES^4 + 9.3539e-08*AES^5 - 0.0024*GR$
5	**Condition**	GR < -3 and 15 ≤ AES < 55
	Equation	$CSOC = 1/(-0.18739 + 0.0014953*AES^{(1.5)} - 1.7461/GR)$
6	**Condition**	GR ≤ 0 and AES < 15
	Equation	$CSOC = exp(1.7713 - 0.12178*AES^{(0.5)}*ln(AES) + 0.14636*GR + 0.11002*GR^2 + 0.0082804*GR^3)$
7	**Condition**	Otherwise
	Equation	CSOC = -173.3 + 34.6*ln(AES) + 1973/AES

E.4.3 Constant-Speed Tire Wear (CSTW)

Table E-17. Medium/Large Automobile Constant-Speed Tire Wear

1	**Condition**	GR ≥ 2.5 and AES<55
	Equation	$CSTW=\exp(-2.39+0.0001564*AES^2+0.01367*AES+1.475*\ln(GR)-0.001586*AES*GR)$
2	**Condition**	(0 < GR < 2.5 and AES < 15) or (-AES/20 ≤ GR <2.5 and 15 ≤ AES <55)
	Equation	$CSTW=0.229+2.65*10^{-6}*AES^3-0.0403*\ln(AES)+0.0214*GR^2+0.00392*AES*GR$
3	**Condition**	(-1.5 < GR ≤ 0 and AES < 15) or (-AES/10 < GR < -AES/20 and 15 ≤ AES <55)
	Equation	$CSTW=0.08+3.0*10^{-6}*AES^3+0.029*GR^2+0.0828*GR+0.000056*AES^2*GR$
4	**Condition**	(GR ≤ -1.5 and AES < 15) or (GR ≤ -AES/10 and 15 ≤ AES <55)
	Equation	$CSTW=\exp(-5.22-0.000771*AES^2+0.0843*GR+2.81*\ln(-GR)-0.00323*AES*GR)$
5	**Condition**	GR ≥ 0.5 and AES ≥ 55
	Equation	$CSTW=1.318+0.000743*AES^2-0.05661*AES+0.01941*GR^2+0.00417*AES*GR$
6	**Condition**	(-AES/10+1 < GR < 0.5 and AES ≥ 55) or (GR < 0.5 and AES ≥ 80)
	Equation	$CSTW=-0.2022+0.000237*AES^2+0.0213*GR^2-1.0322*GR+0.3099*\ln(AES)*GR$
7	**Condition**	otherwise
	Equation	$CSTW=-0.2613+0.000164*AES^2+0.02065*GR^2+0.005452*AES*GR-0.03975*\ln(AES)*GR$

E.4.4 Constant-Speed Maintenance and Repair (CSMR)

Table E-18. Medium/Large Automobile Constant-Speed Maintenance and Repair

1	**Condition**	GR≥0
	Equation	$CSMR=48.4+0.00867*AES^2+0.0577*AES*GR$
2	**Condition**	(-1.5 ≤ GR < 0 and AES ≤ 25) or (GR < 0 and -12.2*GR+4 ≤ AES and 25 < AES < 55)
	Equation	$CSMR=45.19+0.00584*AES^2+0.229*AES+0.0562*AES*GR$
3	**Condition**	(GR < -1.5 and AES ≤ 25) or (GR < 0 and -12.2*GR+4 > AES and 25 < AES < 55)
	Equation	$CSMR=-6.67-0.018*AES^2-23.4*GR$
4	**Condition**	-0.14*AES+3.6 < GR < 0 and AES ≥ 55
	Equation	$CSMR=72.46+0.01373*AES^2-0.7081*AES+0.05597*AES*GR$
5	**Condition**	otherwise
	Equation	$CSMR=-5.415-0.01912*AES^2-23.51*GR$

E.4.5 Constant-Speed Depreciation (CSVD)

Table E-19. Medium/Large Automobile Constant-Speed Vehicle Depreciation

1	**Condition**	all
	Equation	CSVD=1.725+0.001892*AES-0.311*ln(AES)

E.4.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-20. Medium/Large Automobile Excess Fuel Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCFC=0.008*CSMAX^3$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCFC=0.03401+0.1902*CSMAX+4491*10^{-8}*CSMAX^3$

E.4.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-21. Medium/Large Automobile Excess Oil Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCOC=0.00004*CSMAX^3$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCOC=0.000801+0.000869*CSMAX-1617*10^{-8}*CSMAX^2+197*10^{-8}*CSMAX^3$

E.4.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-22. Medium/Large Automobile Excess Tire Wear Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCTW=0.0012*CSMAX^2$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCTW=exp(-6.64+1.947*ln(CSMAX)-9909*10^{-8}*CSMAX^2)$

E.4.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-23. Medium/Large Automobile Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCMR=0.0016*CSMAX^2$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCMR=exp(-6.277+0.007347*CSMAX+1.876*ln(CSMAX)-7275*10^{-8}*CSMAX^2)$

E.4.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-24. Medium/Large Automobile Depreciation Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCD=0.0004*CSMAX
2	**Condition**	5 ≤ CSMAX < 50
	Equation	SCCD=0.001+0.0002*CSMAX
3	**Condition**	CSMAX ≥ 50
	Equation	$SCCD=exp(-4.973+0.000228*CSMAX^2)$

E.4.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-25. Medium/Large Automobile Excess Fuel Consumption Due to Curves

1	**Condition**	$DCA \le 5$ and $AES \le 1/(-0.0137 + 0.0123*DCA^{0.5} + 0.0299/DCA^{0.5})$
	Equation	$CFC = MAX(0, -0.34211 + 0.28291*DCA + 0.014828*AES - 0.016971*DCA^2 - 0.00024465*AES^2 - 0.0047869*DCA*AES)$
2	**Condition**	$DCA > 5$ and $AES \le 1/(-0.0137 + 0.0123*DCA^{0.5} + 0.0299/DCA^{0.5})$
	Equation	$CFC = MAX(0, -0.79434 + 1.1403*LN(DCA) + 0.052408*AES - 0.1933*(LN(DCA))^2 - 0.00060403*AES^2 - 0.028889*AES*LN(DCA))$
3	**Condition**	$AES > 1/(-0.0137 + 0.0123*DCA^{0.5} + 0.0299/DCA^{0.5})$
	Equation	$CFC = MAX(0, EXP(-18.864 - 0.02183*DCA^{(1.5)} + 2.6113*DCA^{(0.5)} + 1.80792*AES^{(0.5)}))$

E.4.12 Excess Tire Wear Due to Curves (CTW)

Table E-26. Medium/Large Automobile Excess Tire Wear Due to Curves

1	**Condition**	$(DCA \ge 16$ and $AES \ge (-0.031746*DCA^2 +0.74603*DCA +21.19))$ or $(6 \le DCA < 16$ and $AES \ge (45 - 1.9167*DCA + 0.041667*DCA^2))$ or $(DCA < 6$ and $AES \ge (-442.3 + 2959.4/DCA^{(0.5)} - 6735.1/DCA + 6810.6/DCA^{(1.5)} - 2582.5/DCA^2))$
	Equation	CTW = MAX(0, 519464*EXP(-EXP(-(DCA - 48.665)/18.647) - (DCA - 48.665)/18.647 + 1) * EXP(-EXP(-(AES - 127.84)/39.862) - (AES - 127.84)/39.862 + 1))
2	**Condition**	$(DCA \ge 16$ and $AES < (-0.031746*DCA^2 +0.74603*DCA +21.19))$ or $(6 \le DCA < 16$ and $AES < (45 - 1.9167*DCA + 0.041667*DCA^2))$
	Equation	$CTW = MAX(0, -31.7 + 20.767*LN(DCA) + 22.783*LN(AES) - 2.5841*(LN(DCA))^2 - 3.9522*(LN(AES))^2 - 4.4831*LN(DCA)*LN(AES))$
3	**Condition**	$DCA < 6$ and $AES < (-442.3 + 2959.4/DCA^{(0.5)} - 6735.1/DCA + 6810.6/DCA^{(1.5)} - 2582.5/DCA^2)$
	Equation	$CTW = MAX(0, -4.4955 + 4.542*DCA + 0.088792*AES - 0.27253*DCA^2 - 0.00042329*AES^2 - 0.07399*DCA*AES)$

E.4.13 Excess Maintenance and Repair Due to Curves

Table E-27. Medium/Large Automobile Excess Maintenance and Repair Due to Curves

1	**Condition**	(DCA > 12 and AES ≥ (-0.5*DCA + 30)) or (DCA < 12 and AES ≥ (-2.3636*DCA + 52.364))
	Equation	CMR = MAX(0, EXP(-37.927 + 3.2935*LN(DCA) + 1.8096/DCA + 7.8477*LN(AES)))
2	**Condition**	5 ≤ DCA ≤ 10 and (-1*DCA + 20) ≤ AES ≤ (-1*DCA - 25)
	Equation	CMR = 0.1
3	**Condition**	Otherwise
	Equation	CMR = 0

E.5 4-Tire Trucks

E.5.1 Constant-Speed Fuel Consumption (CSFC)

Table E-28. 4-Tire Truck Constant-Speed Fuel Consumption

1	**Condition**	GR ≥ 0 and 20 < AES < 55
	Equation	CSFC = 115.41 - 3.6397*AES + 7.0832*GR + 0.050662*AES^2 - 0.34401*GR^2 + 0.096956*AES*GR
2	**Condition**	GR ≥ 0 and AES ≤ 20
	Equation	CSFC = 120.7 + -5.0201*AES + 0.1088*AES^2 + 9.8816*GR - 1.3755*GR^2 + 0.11582*GR^3
3	**Condition**	GR < 0 and AES ≤ 10
	Equation	CSFC = 161.2 - 6.622*AES - 87.758*ln(AES)/AES - 1.0889*GR^2 - 0.13217*GR^3
4	**Condition**	GR < 0 and 10 < AES ≤ 20
	Equation	CSFC = 106.31 - 2.7456*AES + 5.0147*GR - 0.001281*AES^2 + 0.94555*GR^2 + 0.19499*AES*GR
5	**Condition**	GR < 0 and 20 < AES < 55
	Equation	CSFC = 351.5 - 184.42*ln(AES) + 0.71838*GR + 28.297*$(\ln(AES))^2$ + 1.0105*GR^2 + 2.8947*GR*ln(AES)
6	**Condition**	GR ≥ 1.5 and AES ≥ 55
	Equation	CSFC = 110.4 + 0.000249*AES^3 - 18.93*ln(AES) + 8.06*GR
7	**Condition**	-2.5 ≤ GR < 1.5 and AES ≥ 55
	Equation	CSFC = (28.77 + 0.183655*AES + 3.34032*GR) / (1 - 0.0074966*AES - 0.049703*GR)
8	**Condition**	Otherwise
	Equation	CSFC = exp(2.784 + 0.02014*AES + 0.06881*GR)

E.5.2 Constant-Speed Oil Consumption (CSOC)

Table E-29. 4-Tire Truck Constant-Speed Oil Consumption

1	**Condition**	GR > 0 and AES < 50
	Equation	$CSOC=exp(2.47-0.604*ln(AES)-0.00994*GR^2+0.277*GR-0.001248*AES*GR)$
2	**Condition**	GR > 0 and 50 ≤ AES ≤ 70
	Equation	$CSOC=16.41+0.004424*AES^2-0.5255*AES+1.296*GR-0.2664*ln(AES)*GR$
3	**Condition**	GR > 0 and AES > 70
	Equation	$CSOC=16.41+0.004424*AES^2-0.5255*AES+0.19*GR$
4	**Condition**	min(-3.5, -AES/6.0) < GR≤ 0 and AES < 50
	Equation	$CSOC=8.45+0.0000352*AES^3-0.00567*AES^2+0.370*AES-4.12*ln(AES)$
5	**Condition**	GR < min(-3.5, -AES/6.0) and AES < 50
	Equation	$CSOC=exp(0.92-0.000295*AES^2-0.751*ln(AES) -0.0269*GR^2-0.584*GR)$
6	**Condition**	otherwise
	Equation	$CSOC=16.41+0.004424*AES^2-0.5255*AES$

E.5.3 Constant-Speed Tire Wear

Table E-30. 4-Tire Truck Constant-Speed Tire Wear

1	**Condition**	GR ≥ 2.5 and AES < 55
	Equation	CSTW = EXP(-2.08 + 0.0001517*AES^2 + 0.012*AES + 1.367*LN(GR) - 0.001389*AES*GR)
2	**Condition**	(0 < GR < 2.5 and AES < 15) or (-AES/20 < GR < 2.5 and 15 ≤ AES < 55)
	Equation	CSTW = 0.297 + 2.9*10$^{(-6)}$*AES^3 - 0.0421*LN(AES) + 0.0234*GR^2 + 0.00429*AES*GR
3	**Condition**	(-2.5 < GR ≤ 0 and AES < 15) or (-AES/10 < GR ≤ -AES/20 and 15 ≤ AES < 55)
	Equation	CSTW = 0.1294 + 3.64*10$^{(-6)}$*AES^3 + 0.0324*GR^2 + 0.1085*GR + 0.0000631*AES^2*GR
4	**Condition**	(GR ≤ -2.5 and AES < 15) or (GR < -AES/10 and 15 ≤ AES < 55)
	Equation	CSTW = EXP(-5.45 - 4.13*10$^{(-6)}$*AES^3 - 0.01377*AES + 2.79*LN(-GR))
5	**Condition**	GR ≥ 0.5 and AES ≥ 55
	Equation	CSTW = 1.365 + 0.000736*AES^2 - 0.05471*AES + 0.0197*GR^2 + 0.004395*AES*GR
6	**Condition**	((-AES/10+1) < GR < 0.5 and AES ≥ 55) or (GR < 0.5 and AES ≥ 80)
	Equation	CSTW = ABS(-0.1554 + 0.000258*AES^2 + 0.0205*GR^2 - 0.05138*GR + 0.005058*AES*GR)
7	**Condition**	Otherwise
	Equation	CSTW = MAX(0.01, -0.2177 + 0.000208*AES^2 + 0.02376*GR^2 + 0.005895*AES*GR - 0.03288*LN(AES)*GR)

E.5.4 Constant-Speed Maintenance and Repair

Table E-31. 4-Tire Truck Constant-Speed Maintenance and Repair

1	**Condition**	GR ≥ 0
	Equation	CSMR=49.2+0.00881*AES^2+0.0545*AES*GR
2	**Condition**	(-1.5 ≤ GR < 0 and AES ≤ 20) or (GR < 0 and 20 < AES < 55 and AES≥-10*GR+6)
	Equation	CSMR=46.0+0.00595*AES^2+0.231*AES+0.0531*AES*GR
3	**Condition**	(GR < -1.5 and AES ≤ 20) or (GR < 0 and 20 < AES < 55 and AES < -10*GR+6)
	Equation	CSMR=-12.43-0.019*AES^2-23.5*GR
4	**Condition**	(GR <0 and AES ≥ 55 and GR > -0.1*AES+0.75) or (GR < 0 and AES>70)
	Equation	CSMR=72.36+0.01373*AES^2-0.6841*AES+0.0532*AES*GR
5	**Condition**	otherwise
	Equation	CSMR=-13.83-0.0197*AES^2-24.01*GR

E.5.5 Constant-Speed Depreciation (CSVD)

Table E-32. 4-Tire Truck Constant-Speed Vehicle Depreciation

1	**Condition**	all
	Equation	CSVD = 0.742+0.000589*AES-0.1307*ln(AES)

E.5.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-33. 4-Tire Truck Excess Fuel Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCFC=0.00904*CSMAX^{3}$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCFC=0.8137+0.1576*CSMAX+7327*10^{-8}*CSMAX^{3}$

E.5.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-34. 4-Tire Truck Excess Oil Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCOC=0.0002*CSMAX^{2}$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCOC=exp(-6.242+0.5935*ln(CSMAX)+0.000131*CSMAX^{2})$

E.5.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-35. 4-Tire Truck Excess Tire Wear Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCTW=0.0012*CSMAX^{2}$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCTW=exp(-6.568+1.906*ln(CSMAX)- 7502*10^{-8}*CSMAX^{2})$

E.5.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-36. 4-Tire Truck Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCMR=0.0016*CSMAX^{2}$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCMR=exp(-6.39+1.958*ln(CSMAX)- 1781*10^{-8}*CSMAX^{2})$

E.5.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-37. 4-Tire Truck Excess Depreciation Due to Speed Variability

1	**Condition**	CSMAX < 60
	Equation	SCCD=0.0002*CSMAX
2	**Condition**	CSMAX ≥ 60
	Equation	SCCD=exp(-5.0007+0.000162*$CSMAX^2$)

E.5.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-38. 4-Tire Truck Excess Fuel Consumption Due to Curves

1	**Condition**	(DCA < 6 and AES ≥ (-0.5682*DCA^2 + 0.75*DCA + 55.818)) or (DCA ≥ 6 and AES ≥ (-0.0055*DCA^2 - 0.7634*DCA + 43.597))
	Equation	CFC = MAX(0, EXP(779.63 - 1.2743*DCA + 3.1889*$DCA^{(0.5)}$*LN(DCA) - 2.9306*$DCA^{(0.5)}$ - 25.106*$AES^{(0.5)}$ - 10108.5/$AES^{(0.5)}$ + 10588.5*LN(AES)/AES))
2	**Condition**	(DCA ≥ 10 and AES ≤ (57.993 + 1.1162*DCA - 13.963*$DCA^{0.5}$)) or (8 ≤ DCA < 10 and AES ≤ 25)
	Equation	CFC = MAX(0, -0.45381 + 0.98231*LN(DCA) + 0.10049*AES - 0.15*$(LN(DCA))^2$ - 0.0011603*AES^2 - 0.046122*AES*LN(DCA))
3	**Condition**	4 ≤ DCA < 8 and AES ≤ (-2.5*DCA + 45)
	Equation	CFC = MAX(0, -2.0296 + 2.4402*LN(DCA) + 0.087398*AES - 0.50234*$(LN(DCA))^2$ - 0.0012841*AES^2 - 0.036879*AES*LN(DCA))
4	**Condition**	(2 ≤ DCA < 4 and AES ≤ 35) or (DCA < 2 and AES ≤ (2.5*DCA + 30))
	Equation	CFC = MAX(0, EXP(0.0010091 - 5.4673/DCA^2 - 0.082805*AES + 0.011991*AES^2 - 0.0018375*$AES^{(2.5)}$))
5	**Condition**	Otherwise
	Equation	CFC = 0

E.5.12 Excess Tire Wear Due to Curves (CTW)

Table E-39. 4-Tire Truck Excess Tire Wear Due to Curves

1	**Condition**	(DCA ≥ 16 and AES ≥ (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (6 ≤ DCA < 16 and AES ≥ (35 - 125/DCA + 750/DCA^2)) or (DCA < 6 and AES ≥ (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3))
	Equation	CTW = MAX(0, 450515*EXP(-EXP(-(DCA - 49.07)/18.816) - (DCA - 49.07)/18.816 + 1) * EXP(-EXP(-(AES - 124.84)/38.88) - (AES - 124.84)/38.89 + 1))
2	**Condition**	DCA ≤ 16 and AES < (0.02381*DCA^2 - 1.4524*DCA + 42.143)
	Equation	CTW = MAX(0, -13.126 + 79.095/DCA + 254.26/AES - 39.567/DCA^2 - 694.97/AES^2 - 217.62/(DCA*AES))
3	**Condition**	(6 ≤ DCA < 16 and AES < (35 - 125/DCA + 750/DCA^2)) or (DCA < 6 and AES < (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3)
	Equation	CTW = MAX(0, -2.743 + 3.5215*DCA + 0.077273*AES - 0.16376*DCA^2 - 0.00069592*AES^2 - 0.064592*DCA*AES)

E.5.13 Excess Maintenance and Repair Due to Curves

Table E-40. 4-Tire Truck Excess Maintenance and Repair Due to Curves

1	**Condition**	(DCA ≥ 12 and AES ≥ (-0.45*DCA + 30.4)) or (DCA < 12 and AES ≥ (-2.2727*DCA + 52.273))
	Equation	CMR = MAX(0, EXP(594.56 - 0.021279*DCA$^{(1.5)}$ + 2.6656*DCA$^{(0.5)}$ - 19.444*AES$^{(0.5)}$ - 7777/AES$^{(0.5)}$ + 8121.8*LN(AES)/AES))
2	**Condition**	(3.5 < DCA < 8.5 and 17.5 ≤ AES < 22.5) or (4.5 < DCA < 10.5 and 12.5 ≤ AES ≤ 17.5) or (7.5 < DCA < 12.5 and 7.5 < AES <= 12.5)
	Equation	CMR = 0.1
3	**Condition**	Otherwise
	Equation	CMR = 0

E.6 6-Tire Truck

E.6.1 Constant-Speed Fuel Consumption (CSFC)

Table E-41. 6-Tire Truck Constant-Speed Fuel Consumption

1	**Condition**	$GR \geq 0$ and $AES < 55$
	Equation	$CSFC = 298.60 - 13.131*AES + 53.987*GR + 0.30096*AES^2 - 4.7321*GR^2 - 0.88407*AES*GR - 0.0020906*AES^3 + 0.22739*GR^3 + 0.02875*AES*GR^2 + 0.0045428*AES^2*GR$
2	**Condition**	$GR < 0$ and $AES < 55$
	Equation	$CSFC = 273.05 - 9.2427*AES +58.195*GR + 0.14718*AES^2 + 6.7665*GR^2 - 1.3785*AES*GR - 0.00046068*AES^3 + 0.13884*GR^3 - 0.079555*AES*GR^2 + 0.012622*AES^2*GR$
3	**Condition**	$GR \geq 1.5$ and $AES \geq 55$
	Equation	$CSFC = 361.11 - 8.1978*AES + 11.186*GR + 0.077607*AES^2-0.27665*GR^2 - 0.035211*AES*GR$
4	**Condition**	$GR < 1.5$ and $AES \geq 55$
	Equation	$CSFC = 101.5 + 0.000186*AES^3 + 1.102*GR^2 + 18.22*GR$

E.6.2 Constant-Speed Oil Consumption (CSOC)

Table E-42. 6-Tire Truck Constant-Speed Oil Consumption

1	**Condition**	$GR > 0$ and $AES < 55$
	Equation	$CSOC = \exp(3.8424 - 0.93964*\ln(AES) - 1.7418/AES + 0.80327*GR^{(0.5)})$
2	**Condition**	$GR > 0$ and $AES \geq 55$
	Equation	$CSOC = 51.76 + 0.002513*AES^2 - 14.29*\ln(AES)+ 0.7485*GR$
3	**Condition**	($-1.5 < GR \leq 0$ and $AES < 55$) or ($-AES/10 \leq GR \leq 0$ and $AES < 55$)
	Equation	$CSOC = 13.98 + 0.0000603*AES^3 - 0.00857*AES^2 + 0.523*AES - 6.17*\ln(AES)$
4	**Condition**	$GR < -AES/10$ and $AES \geq 70$
	Equation	$CSOC = \exp(1.41 + 0.000519*AES^2 - 0.0845*AES - 0.0344*GR^2 - 0.649*GR)$
5	**Condition**	Otherwise
	Equation	$CSOC = 51.76 + 0.002513*AES^2 - 14.29*\ln(AES)$

E.6.3 Constant-Speed Tire Wear (CSTW)

Table E-43. 6-Tire Truck Constant-Speed Tire Wear

1	**Condition**	GR ≥2.5 and AES<55
	Equation	$CSTW=\exp(-1.572+0.0000943*AES^2+0.01509*AES+1.65*\ln(GR)-0.001535*AES*GR)$
2	**Condition**	GR ≥2.5 and AES ≥ 55
	Equation	$CSTW=2.206+0.001267*AES^2-0.09683*AES+0.07733*GR^2+0.01096*AES*GR$
3	**Condition**	(0 < GR < 2.5 and AES<15) or (-AES/25 < GR <2.5 and AES≥15)
	Equation	$CSTW=0.353+4.5*10^{-6}*AES^3-0.0556*\ln(AES)+0.0855*GR^2+0.01012*AES*GR$
4	**Condition**	(-1.5 < GR ≤ 0 and AES < 15) or (-AES/14 < GR < -AES/25 and AES ≥ 15)
	Equation	$CSTW=0.104+5.37*10^{-8}*AES^4+0.0001578*AES^2+0.1282*GR^2+$ $0.222*GR+0.000168*AES^2*GR$
5	**Condition**	otherwise
	Equation	$CSTW=\exp(-3.16-3.35*10^{-6}*AES^3-0.0308*AES+2.28*\ln(-GR)-0.00377*AES*GR)$

E.6.4 Constant-Speed Maintenance and Repair (CSMR)

Table E-44. 6-Tire Truck Constant-Speed Maintenance and Repair

1	**Condition**	-4 ≤ GR ≤ -1 and AES > $(-1.6667*GR^3 - 17.5*GR^2 -70.833*GR -45)$ and AES < $(-1.6667*GR^3 - 17.5*GR^2 -70.833*GR -40)$
	Equation	$CSMR = 1/(0.96223 + 2.3017e-06*AES^3 - 0.33129*\exp(AES/44.4878) + 0.48203/GR - 0.00029083*\exp(-GR))$
2	**Condition**	(GR ≥ -1) or (GR < -1 and AES ≥ $(-1.6667*GR^3 - 17.5*GR^2 -70.833*GR -40)$)
	Equation	$CSMR = 44.2 + 0.01147*AES^2 + 0.1462*AES*GR$
3	**Condition**	Otherwise
	Equation	$CSMR = -0.722 - 0.00697*AES^2 - 15.9*GR$

E.6.5 Constant-Speed Depreciation (CSVD)

Table E-45. 6-Tire Truck Constant Speed Vehicle Depreciation

1	**Condition**	AES < 55
	Equation	$CSVD=1.126+0.0028*AES-0.247*\ln(AES)$
2	**Condition**	AES ≥ 55
	Equation	$CSVD=0.2006+4.936/AES$

E.6.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-46. 6-Tire Truck Excess Fuel Consumption Due to Speed Variability

1	**Condition**	$CSMAX < 5$
	Equation	$SCCFC=0.1184*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCFC=3.09+0.02843*CSMAX^2$

E.6.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-47. 6-Tire Truck Excess Oil Consumption Due to Speed Variability

1	**Condition**	$CSMAX < 5$
	Equation	$SCCOC=0.00068*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCOC=exp(-5.069+0.6392*ln(CSMAX)+0.000169*CSMAX^2)$

E.6.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-48. 6-Tire Truck Excess Tire Wear Due to Speed Variability

1	**Condition**	$CSMAX < 5$
	Equation	$SCCTW=0.0016*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCTW=exp(-6.387+1.984*ln(CSMAX)-988*10^{-7}*CSMAX^2)$

E.6.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-49. 6-Tire Truck Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	$CSMAX \leq 5$
	Equation	$SCCMR=0.0012*CSMAX^2$
2	**Condition**	$CSMAX>5$
	Equation	$SCCMR=exp(-6.427+0.01826*CSMAX+1.758*ln(CSMAX)-0.000103*CSMAX^2)$

E.6.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-50. 6-Tire Truck Excess Depreciation Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCD=0.0004*CSMAX
2	**Condition**	$5 \leq$ CSMAX < 40
	Equation	SCCD=0.001429+0.000221*CSMAX
3	**Condition**	CSMAX $\geq$ 40
	Equation	SCCD=exp(-4.957+0.000294*CSMAX^2)

E.6.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-51. 6-Tire Truck Excess Fuel Consumption Due to Curves

1	**Condition**	(DCA $\geq$ 10 and AES >= (27.9 - 0.0144*DCA^2 + 300/DCA^2)) or (2 $\leq$ DCA < 10 and AES $\geq$ (1/(0.0127 + 0.00484*DCA - 0.000675*DCA^2 + 3.97e-05 * DCA^3))) or (DCA < 2 and AES $\geq$ (1/(0.0286 + 0.00429*DCA - 0.00429*DCA^2)))
	Equation	CFC = MAX(0, EXP(-50.349 - 0.98363*DCA - 0.05974*DCA^2 + 59.476*EXP(DCA/ 31.649) - 90.158/AES$^{(0.5)}$))
2	**Condition**	DCA $\geq$ 5 and AES $\leq$ (27.9 - 0.0144 * DCA^2 + 300/DCA^2)
	Equation	CFC = MAX(0, -9.7649 + 7.88*LN(DCA) + 6.036*LN(AES) - 1.0423*(LN(DCA))^2 - 1.053*(LN(AES))^2 - 1.464*LN(DCA)*LN(AES))
3	**Condition**	1 < DCA < 5 and AES $\leq$ (30 + 70/DCA - 100/DCA^2)
	Equation	CFC = MAX(0, EXP(1.604 - 4.6423/DCA$^{(1.5)}$ - 0.000062414*AES^3))
4	**Condition**	Otherwise
	Equation	CFC = 0

E.6.12 Excess Tire Wear Due to Curves (CTW)

Table E-52. 6-Tire Truck Excess Tire Wear Due to Curves

1	**Condition**	(DCA ≥ 16 and AES ≥ (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (6 ≤ DCA < 16 and AES ≥ (35 - 125/DCA + 750/DCA^2)) or (DCA < 6 and AES ≥ (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3))
	Equation	CTW = MAX(0, 377675*EXP(-EXP(-(DCA - 51.703)/19.791) -(DCA - 51.703)/19.791 + 1) * EXP(-EXP(-(AES - 120.93)/37.611) - (AES - 120.93)/37.611 + 1))
2	**Condition**	(DCA ≥ 16 and AES < (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (6 ≤ DCA < 16 and AES < (35 - 125/DCA + 750/DCA^2))
	Equation	CTW = MAX(0, -26.586 + 17.42*LN(DCA) + 19.303*LN(AES) - 2.1482*(LN(DCA))^2 - 3.3487*(LN(AES))^2 - 3.81*LN(DCA)*LN(AES))
3	**Condition**	DCA < 6 and AES < (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3)
	Equation	CTW = MAX(0, -4.0066 + 3.8372*DCA + 0.11043*AES - 0.2262*DCA^2 - 0.0011358*AES^2 - 0.064529*DCA*AES)

E.6.13 Excess Maintenance and Repair Due to Curves

The fourth equation for 6-Tire Truck excess maintenance and repair due to curves is incremental - the condition is true when certain other conditions are true and the equation adds value to the existing CMR value.

Table E-53. 6-Tire Truck Excess Maintenance and Repair Due to Curves

1	**Condition**	DCA ≥ 8 and AES ≥ (-0.0038*DCA^2 - 0.3106*DCA + 27.272)
	Equation	CMR = MAX(0, EXP(9.6157 + 0.12975*DCA - 157.95/DCA^2 + 7095.5*EXP(-DCA) - 106.49*LN(AES)/AES))
2	**Condition**	DCA < 8 and AES ≥ (-0.625*DCA^2 + 3.125*DCA + 40)
	Equation	CMR = MAX(0, EXP(-314.6 + 2.5973*DCA*LN(DCA) - 1.4569*DCA^2 + 0.30227*DCA$^{(2.5)}$ + 2642/LN(AES) - 2565.9/AES$^{(0.5)}$))
3	**Condition**	(1 ≤ DCA ≤ 3 and (-10*DCA + 37.5) < AES < (10*DCA + 2.5)) or (3 < DCA ≤ 5 and AES < 32.5) or (5 < DCA < 8 and AES < (0.8333*DCA^2 - 14.167*DCA +85)) or (DCA ≥ 8 and AES < (-0.0038*DCA^2 - 0.3106*DCA + 24.5))
	Equation	CMR = 0.1
4	**Condition**	DCA > 4.5 and 12.5 < AES < (-0.35*DCA^2 + 3.85*DCA + 12)
	Equation	CMR = CMR + 0.1
5	**Condition**	Otherwise
	Equation	CMR = 0

E.7 3+ Axle Single-Unit Truck

E.7.1 Constant-Speed Fuel Consumption (CSFC)

Table E-54. 3+ Axle Single-Unit Truck Constant-Speed Fuel Consumption

1	**Condition**	$GR \geq 3$ and $AES \leq 20$
	Equation	$CSFC = 68.536 + 12.823*AES + 122.45*GR + 0.023896*AES^2 + 0.36758*GR^2 - 6.2014*AES*GR$
2	**Condition**	$3 \geq GR \geq 0$ and $AES \leq 20$
	Equation	$CSFC = 254 - 3.0854*AES - 2.177*GR - 0.063346*AES^2 + 24.848*GR^2 + 4.3101*AES*GR + 0.0012816*AES^3 - 1.2432*GR^3 - 1.6437*AES*GR^2 + 0.0013556*AES^2*GR$
3	**Condition**	$GR < 0$ and $AES \leq 20$
	Equation	$CSFC = (259.66 - 19.925*AES+ 0.49931*AES^2 - 0.0045651*AES^3 - 1.5876*GR) / (1 - 0.058535*AES + 0.00077356*AES^2 - 0.14916*GR + 0.024241*GR^2)$
4	**Condition**	$GR > 3$ and $AES > 20$
	Equation	$CSFC = 290.45 - 2.598*AES + 25.823*GR + 0.024983*AES^2 - 2.2654*GR^2 + 0.21897*AES*GR$
5	**Condition**	$3 \geq GR \geq 0$ and $AES > 20$
	Equation	$CSFC = 1208.8 - 586.87*LN(AES) + 80.955*(\ln(AES))^2 + 93.99*GR - 13.477*GR^2$
6	**Condition**	$0 > GR \geq -3$ and $AES > 20$
	Equation	$CSFC = \exp(6.0673 - 0.1139*AES + 0.023622*AES*\ln(AES) + 0.79191*GR - 0.022171*GR^3)$
7	**Condition**	$GR < -3$ and $AES > 20$
	Equation	$CSFC = (-1.3978 / (1 + (((AES - 40.215) / -11.403)^2))) + (47.024 / (1 + (((GR + 0.01611)/5.4338)^2))) + (-26.724 / (1 + (((AES - 40.215) / -11.403)^2))) * (1 / (1 + (((GR + 0.01611) / 5.4338)^2)))$

E.7.2 Constant-Speed Oil Consumption (CSOC)

Table E-55. 3+ Axle Single-Unit Truck Constant-Speed Oil Consumption

1	**Condition**	GR > 0 and AES<55
	Equation	CSOC=exp(4.36+0.00711*AES-0.869*ln(AES)-0.01712*GR^2+0.338*GR)
2	**Condition**	min(-1.5,-AES/12.5) < GR ≤ 0 and AES<55
	Equation	CSOC=20.2+0.0000724*AES^3-0.0103*AES^2+0.662*AES-8.52*ln(AES)
3	**Condition**	GR ≤ min(-1.5,-AES/12.5) and AES < 55
	Equation	CSOC=exp(1.77+0.00055*AES^2-0.0769*AES-0.0343*GR^2-0.646*GR)
4	**Condition**	GR > 0 and AES ≥ 55
	Equation	CSOC=22.85+0.006514*AES^2-0.7188*AES+1.615*GR
5	**Condition**	(-AES/12.5 ≤ GR ≤ 0 and AES ≥ 55) or (GR ≤0 and AES ≥ 90)
	Equation	CSOC=22.85+0.006514*AES^2-0.7188*AES
6	**Condition**	otherwise
	Equation	CSOC=exp(1.77+0.00055*AES^2-0.0769*AES-0.0343*GR^2-0.646*GR)

E.7.3 Constant-Speed Tire Wear (CSTW)

Table E-56. 3+ Axle Single-Unit Truck Constant-Speed Tire Wear

1	**Condition**	GR ≥ 2.5 and AES<55
	Equation	CSTW=exp(-1.71+0.0000511*AES^2+0.01134*AES+1.575*ln(GR)-0.001038*AES*GR)
2	**Condition**	GR ≥ 2.5 and AES ≥ 55
	Equation	CSTW=1.085+0.000405*AES^2-0.03274*AES+0.05955*GR^2+0.00577*AES*GR
3	**Condition**	(-0.5 < GR < 2.5 and AES<15) or (-AES/30 < GR <2.5 and AES≥15)
	Equation	CSTW=0.0896+0.0001308*AES^2+0.0552*GR^2+0.1181*GR+0.00402*AES*GR
4	**Condition**	-AES/20 < GR ≤ -AES/30 and AES≥15
	Equation	CSTW=0.0345+0.000387*AES^2+0.257*GR^2+0.01988*AES*GR
5	**Condition**	otherwise
	Equation	CSTW=exp(-3.30-0.0275*AES+0.1868*GR+2.92*ln(-GR)-0.00275*AES*GR)

E.7.4 Constant-Speed Maintenance and Repair (CSMR)

Table E-57. 3+ Axle Single-Unit Truck Constant-Speed Maintenance and Repair

1	**Condition**	$-4 \le GR \le -1$ and $AES > (-1.6667*GR^3 - 17.5*GR^2 - 75.833*GR - 45)$ and $AES < (-1.6667*GR^3 - 17.5*GR^2 - 75.833*GR - 40)$
	Equation	$CSMR = 1046.8 - 499.21*\ln(AES) + 106.76*(\ln(AES))^2 + 601.98*GR + 154.36*GR^2 + 15.039*GR^3$
2	**Condition**	$(GR \ge -1)$ or $(GR < -1$ and $AES \ge (-1.6667*GR^3 - 17.5*GR^2 - 75.833*GR - 40))$
	Equation	$CSMR = 46 + 0.008*AES^2 + 0.146*AES*GR$
3	**Condition**	Otherwise
	Equation	$CSMR = 1.6996 + 0.094776*AES - 0.016324*AES^2 + 0.00037673*AES^3 - 4.0767e\text{-}06*AES^4 + 1.4984e\text{-}08*AES^5 - 14.684*GR$

E.7.5 Constant-Speed Depreciation (CSVD)

Table E-58. 3+ Axle Single-Unit Constant-Speed Vehicle Depreciation

1	**Condition**	$AES < 55$
	Equation	$CSVD=1.126+0.00279*AES-0.247*\ln(AES)$
2	**Condition**	otherwise
	Equation	$CSVD=0.2006+4.936/AES$

E.7.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-59. 3+ Axle Single-Unit Truck Excess Fuel Consumption Due to Speed Variability

1	**Condition**	$CSMAX < 5$
	Equation	$SCCFC=0.174*CSMAX^2$
2	**Condition**	$CSMAX \ge 5$
	Equation	$SCCFC=4.477+0.03862*CSMAX^2$

E.7.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-60. 3+ Axle Single-Unit Truck Excess Oil Consumption Due to Speed Variability

1	**Condition**	$CSMAX < 5$
	Equation	$SCCOC=0.00136*CSMAX^2$
2	**Condition**	$CSMAX \ge 5$
	Equation	$SCCOC=\exp(-4.408+0.6632*\ln(CSMAX)+0.000148*CSMAX^2)$

E.7.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-61. 3+ Axle Single-Unit Truck Excess Tire Wear Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCTW=0.0012*CSMAX^2$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCTW=exp(-6.595+1.918*ln(CSMAX)-6855*10^{-8}*CSMAX^2)$

E.7.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-62. 3+ Axle Single-Unit Truck Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCMR=0.0008*CSMAX^2$
2	**Condition**	CSMAX ≥ 5
	Equation	$SCCMR=exp(-7.446-0.005514*CSMAX+2.212*ln(CSMAX)+ 5075*10^{-8}*CSMAX^2)$

E.7.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-63. 3+ Axle Single-Unit Truck Depreciation Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCD=0.0006*CSMAX
2	**Condition**	5 ≤ CSMAX < 55
	Equation	SCCD=0.001+0.0004*CSMAX
3	**Condition**	CSMAX ≥ 55
	Equation	$SCCD=exp(-4.439+0.000231*CSMAX^2)$

E.7.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-64. 3+ Axle Single-Unit Truck Excess Fuel Consumption Due to Curves

1	**Condition**	(DCA ≥ 6 and AES ≥ (44.375 - 1.8236*DCA + 0.02044*DCA^2 + 0.0018571*DCA^2 - 0.000053954*DCA^2)) or (6 > DCA ≥ 2 and AES ≥ (39.5 + 4.1667*DCA - 0.83333*DCA^2))
	Equation	CFC = EXP(371.346 + 5.1878*LN(DCA) + 10.1521/DCA$^{(0.5)}$ - 12.1424*AES$^{(0.5)}$ - 4915.79/AES$^{(0.5)}$ + 5093.19*LN(AES)/AES))
2	**Condition**	DCA < 2 and AES ≥ (24.5 - 10*DCA + 10*DCA^2)
	Equation	CFC = MAX(0, 1.3873+ 38.977*EXP(-0.5*(((DCA-2.2124)/1.071)^2 + ((AES-102.44)/16.633)^2)))
3	**Condition**	2 ≤ DCA ≤ 16 and AES < 10
	Equation	CFC = MAX(0, -4.0824 + 1.833*DCA - 0.15946*DCA^2 + 0.0044245*DCA^3 + 0.56919*AES - 0.038513*AES^2 + 0.00079158*AES^3)
4	**Condition**	DCA ≤ 1 and AES < 25
	Equation	CFC = 0
5	**Condition**	Otherwise
	Equation	CFC = MAX(0, -8.9743 - 0.099969*DCA +16.366*LN(AES)+ 0.0052265*DCA^2 - 3.6805*(LN(AES))^2 - 0.11371*DCA*LN(AES))

E.7.12 Excess Tire Wear Due to Curves (CTW)

Table E-65. 3+ Axle Single Unit Truck Excess Tire Wear Due to Curves

1	**Condition**	(DCA ≥ 16 and AES ≥ (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (16 > DCA ≥ 6 and AES ≥ (35 - 125/DCA + 750/DCA^2)) or (DCA < 6 and AES ≥ (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^2))
	Equation	CTW = MAX(0, 707192*EXP(-EXP(-(DCA - 44.524)/16.77) - (DCA - 44.524)/16.77 + 1) * EXP(-EXP(-(AES - 132.23)/40.729) - (AES - 132.23)/40.729 + 1))
2	**Condition**	(DCA ≥ 16 and AES < (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (16 > DCA ≥ 6 and AES < (35 - 125/DCA + 750/DCA^2))
	Equation	CTW = MAX(0, 7.4369 + 29.473/DCA + 6.5816*LN(AES) - 541.46/DCA^2 - 3.8133*(LN(AES))^2 + 45.797*(LN(AES))/DCA)
3	**Condition**	DCA < 6 and AES < (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3)
	Equation	CTW = MAX(0, -4.6194 + 4.5401*DCA + 0.10837*AES - 0.26588*DCA^2 - 0.00099725*AES^2 - 0.076619*DCA*AES)

E.7.13 Excess Maintenance and Repair Due to Curves

The third equation for 3+ Axle Single Unit Truck excess maintenance and repair due to curves is used to increment the value for CMR derived from the second equation under certain conditions. These conditions for this may be true when the condition for equation two is true.

Table E-66. 3+ Axle Single Unit Truck Excess Maintenance and Repair Due to Curves

1	**Condition**	$(DCA \geq 10 \text{ and } AES \geq (-0.75*DCA + 40))$ or $(10 > DCA \geq 2 \text{ and } AES \geq (-2.1875*DCA + 54.375))$ or $(DCA < 2 \text{ and } AES \geq (5*DCA^{2}-2.5*DCA+35))$
	Equation	$CMR = MAX(0, EXP(-50.038+ 0.71092*(LN(DCA))^{2} + 0.50522*LN(DCA) - 0.08522*AES + 13.02*LN(AES)))$
2	**Condition**	$(1 \leq DCA \leq 3 \text{ and } (10*DCA + 2.5) \geq AES \geq (-10*DCA + 37.5))$ or $(3 < DCA \leq 5 \text{ and } AES \leq 32.5)$ or $(DCA \geq 14 \text{ and } AES \leq (-0.3125*DCA + 21.875))$ or $(5 < DCA < 14 \text{ and } AES \leq (-1.66667*DCA + 40.8333))$
	Equation	$CMR = 0.1$
3	**Condition**	$4.5 \leq DCA \leq 10.5 \text{ and } AES > (39.3 - 13.497*DCA + 2.215*DCA^{2} - 0.11833*DCA^{3})$ and $AES < (17.5 + 5/(1 + exp(-((DCA - 7.0222)/-0.07845))))$
	Equation	$CMR = CMR + 0.1$
4	**Condition**	Otherwise
	Equation	$CMR = 0$

E.8 3-4 Axle Combination Unit Truck

E.8.1 Constant-Speed Fuel Consumption (CSFC)

Table E-67. 3-4 Axle Combination Unit Truck Constant-Speed Fuel Consumption

1	**Condition**	(AES > 20 and 3 ≥ GR ≥ -3) or (AES ≤ 20 and GR ≥ -3)
	Equation	CSFC = (1087.9 - 576.71*LN(AES) 82.039*(LN(AES))^2 + 22.325*GR) / (1-0.17121*LN(AES) - 0.035147*GR)
2	**Condition**	GR < -3
	Equation	CSFC = -239.17 + 61.115*LN(AES) + 2221.9/AES - 4411.6*EXP(-AES)
3	**Condition**	AES > 20 and GR > 3
	Equation	CSFC = EXP(4.5952 + 0.0049349*AES*LN(AES) + 0.31272*GR)

E.8.2 Constant-Speed Oil Consumption (CSOC)

Table E-68. 3-4 Axle Combination Truck Constant-Speed Oil Consumption

1	**Condition**	GR > 0 and AES < 45
	Equation	CSOC=exp(3.92-0.661*ln(AES)-0.01718*GR^2+0.361*GR-0.000640*AES*GR)
2	**Condition**	GR > 0 and 45 ≤ AES ≤ 70
	Equation	CSOC=78.59+0.003813*AES^2-21.76*ln(AES)+2.1254*GR-0.0109*AES*GR
3	**Condition**	GR > 0 and AES > 70
	Equation	CSOC=78.59+0.003813*AES^2-21.76*ln(AES)+1.41*GR
4	**Condition**	(min(-1.5,-AES/12.5) < GR ≤ 0) or (GR ≤ 0 and AES ≥ 70)
	Equation	CSOC=20.2+0.0000724*AES^3-0.01034*AES^2+0.662*AES-8.52*ln(AES)
5	**Condition**	otherwise
	Equation	CSOC=exp(1.85+0.000458*AES^2-0.0746*AES-0.0336*GR^2-0.638*GR)

E.8.3 Constant-Speed Tire Wear (CSTW)

Table E-69. 3-4 Axle Combination Unit Truck Constant-Speed Tire Wear

1	**Condition**	$GR > 3$
	Equation	$CSTW = 0.27453 - 0.016411*AES + 0.090845*GR + 0.00035502*AES^2 + 0.047978*GR^2 + 0.0042709*AES*GR$
2	**Condition**	$GR < -3$
	Equation	$CSTW = ABS(-0.14758 + 0.01337*AES + 0.0040158*GR - 0.000053182*AES^2 + 0.052391*GR^2 + 0.0044432*AES*GR)$
3	**Condition**	$-3 \leq GR \leq 3$
	Equation	$CSTW = 0.15566 - 0.0058457*AES + 0.041763*GR + 0.00021374*AES^2 + 0.056992*GR^2 + 0.0050156*AES*GR$

E.8.4 Constant-Speed Maintenance and Repair (CSMR)

Table E-70. 3-4 Axle Combination Unit Truck Constant-Speed Maintenance and Repair

1	**Condition**	$-3 \leq GR \leq -1$ and $AES \geq (-7.5*GR^2 - 52.5*GR - 25)$ and $AES < (-7.5*GR^2 - 52.5*GR - 20)$
	Equation	$CSMR = 169.6 + 6.4867*AES + 333.98*GR + 48.825*GR^2$
2	**Condition**	$(GR > -1)$ or $(GR < -1$ and $GR \geq -3$ and $AES \geq (-7.5*GR^2-52.5*GR-20))$
	Equation	$CSMR= 46 + 0.008*AES^2 + 0.146*AES*GR$
3	**Condition**	Otherwise
	Equation	$CSMR = 2.44881 - 0.0404901*AES^{(1.5)} - 15.8112*GR$

E.8.5 Constant-Speed Depreciation (CSVD)

Table E-71. 3-4 Axle Combination Truck Constant-Speed Vehicle Depreciation

1	**Condition**	$AES<55$
	Equation	$CSVD=0.354+0.000974*AES-0.0806*\ln(AES)$
2	**Condition**	otherwise
	Equation	$CSVD=0.05657+1.598/AES$

E.8.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-72. 3-4 Axle Combination Unit Truck Excess Fuel Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCFC=0.324*CSMAX^2
2	**Condition**	CSMAX ≥ 5
	Equation	SCCFC=6.342+0.5855*CSMAX+0.03191*CSMAX^2

E.8.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-73. 3-4 Axle Combination Unit Truck Excess Oil Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCOC=0.00136*CSMAX^2
2	**Condition**	CSMAX ≥ 5
	Equation	SCCOC=exp(-4.408+0.6632*ln(CSMAX)+0.000148*CSMAX^2)

E.8.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-74. 3-4 Axle Combination Unit Truck Excess Tire Wear Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCTW=0.0008*CSMAX^2
2	**Condition**	CSMAX ≥ 5
	Equation	SCCTW=exp(-7.111+2.0276*ln(CSMAX)-0.000102*CSMAX^2)

E.8.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-75. 3-4 Axle Combination Unit Truck Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	SCCMR=0.0012*CSMAX^2
2	**Condition**	CSMAX ≥ 5
	Equation	SCCMR=exp(-6.639+0.006003*CSMAX+1.912*ln(CSMAX))

E.8.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-76. 3-4 Axle Combination Unit Truck Excess Depreciation Due to Speed Variability

1	**Condition**	CSMAX < 60
	Equation	SCCD=0.0002*CSMAX
2	**Condition**	CSMAX ≥ 60
	Equation	SCCD=exp(-5.007+0.000162*CSMAX^2)

E.8.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-77. 3-4 Axle Combination Unit Truck Excess Fuel Consumption Due to Curves

1	**Condition**	DCA < 6 and AES ≤ 20
	Equation	CFC = MAX(0,(-0.069855 + 0.4852*LN(DCA) + 0.029223*LN(AES))/(1-0.30752*LN(DCA) + 0.10364*(LN(DCA))^2 - 0.52169*LN(AES) + 0.10545*(LN(AES))^2))
2	**Condition**	20 < AES ≤ (64 + 0.93749*DCA - 13.928 * DCA$^{(0.5)}$) and DCA < 6
	Equation	CFC = MAX(0, -36.549 + 8.3919*DCA + 19.444*LN(AES) - 0.19172*DCA^2 - 2.6623*(LN(AES))^2 - 1.9932*DCA*LN(AES))
3	**Condition**	20 < AES ≤ (64 + 0.93749*DCA - 13.928 * DCA$^{(0.5)}$) and DCA ≥ 6
	Equation	CFC = MAX(0, -44.639 + 15.079*LN(DCA) + 31.738*LN(AES) - 1.734*(LN(DCA))^2 - 5.305*(LN(AES))^2 - 3.6061*LN(DCA)*LN(AES))
4	**Condition**	DCA > 1 and AES ≥ (67 + 0.93749*DCA - 13.928 * DCA$^{(0.5)}$)
	Equation	CFC = MAX(0, EXP(948774.18 + 1.056802*(LN(DCA))^2 + 11715.15*AES$^{(0.5)}$*LN(AES) + 54041.58*(LN(AES))^2 - 133443.12*AES$^{(0.5)}$ - 268395.66*LN(AES) + 309522.12/LN(AES) - 1311374.33/(AES$^{(0.5)}$)))
5	**Condition**	DCA ≤ 1 and AES ≥ (67 + 0.93749*DCA - 13.928 * DCA$^{(0.5)}$)
	Equation	CFC = MAX(0, (-13.559 - 1.1956*DCA + 0.37772*DCA^2 + 3.5166*LN(AES))/(1 - 0.37771*DCA + 0.1152*DCA^2 - 0.1529*LN(AES)))
6	**Condition**	Otherwise
	Equation	CFC = 0

E.8.12 Excess Tire Wear Due to Curves (CTW)

Table E-78. 3-4 Axle Combination Unit Truck Excess Tire Wear Due to Curves

1	**Condition**	(DCA ≥ 16 and AES ≥ (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (16 > DCA ≥ 6 and AES ≥ (35 - 125/DCA + 750/DCA^2)) or (DCA < 6 and AES ≥ (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3))
	Equation	CTW = MAX(0, 578653*EXP(-EXP(-(DCA - 54.618)/20.44) - (DCA - 54.618)/20.44 + 1) * EXP(-EXP(-(AES - 120.41)/37.427) - (AES - 120.41)/37.427 + 1))
2	**Condition**	(DCA ≥ 16 and AES < (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (16 > DCA ≥ 6 and AES < (35 - 125/DCA + 750/DCA^2))
	Equation	CTW = MAX(0, -26.305 + 16.264*LN(DCA) + 20.114*LN(AES) - 1.7217*(LN(DCA))^2 - 3.4077*(LN(AES))^2 - 4.0945*LN(DCA)*LN(AES))
3	**Condition**	DCA < 6 and AES < (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3)
	Equation	CTW = MAX(0, -3.8937 + 3.8291*DCA + 0.092128*AES - 0.22412*DCA^2 - 0.00082522*AES^2 - 0.064764*DCA*AES)

E.8.13 Excess Maintenance and Repair Due to Curves

Table E-79. 3-4 Axle Combination Unit Truck Excess Maintenance and Repair Due to Curves

1	**Condition**	(DCA ≥ 17.5 and AES ≥ (-0.4*DCA + 29.5)) or (17.5 > DCA ≥ 2.5 and AES ≥ (-1.5*DCA + 48.75)) or (DCA < 2.5 and AES ≥ (4*DCA + 35))
	Equation	CMR = MAX(0, EXP(304.96 - 0.90108*DCA + 2.0321*DCA$^{(0.5)}$*LN(DCA) - 0.70003*LN(DCA) - 41.773*LN(AES) - 1312.1/AES$^{(0.5)}$ + 2080.7/AES))
2	**Condition**	(DCA ≤ 3 and (-6.667*DCA^2 + 38.33*DCA + -22.5) ≥ AES ≥ (6.667*DCA^2 - 38.33*DCA + 62.5)) or (3 < DCA ≤ 6 and AES ≤ 32.5) or (6 < DCA < 10 and AES ≤ (-2.5*DCA + 47.5)) or ((DCA ≥ 10 and AES ≤ (-0.5*DCA + 27.5))
	Equation	CMR = 0.1
3*	**Condition**	(3.5 < DCA < 6.5 and 12.5 < AES < 22.5) or (5.5 < DCA < 12.5 and 7.5 < AES < 17.5)
	Equation	CMR = CMR + 0.1
4	**Condition**	Otherwise
	Equation	CMR = 0

* The third equation for 3-4 Axle Combination Unit Truck excess maintenance and repair due to curves is, under certain conditions, used to increment the CMR value derived from the second equation. Under some circumstances, the conditions for both equation two and equation three will be true.

E.9 5+ Axle Combination Unit Truck

E.9.1 Constant-Speed Fuel Consumption (CSFC)

Table E-80. 5+ Axle Combination Unit Truck Constant-Speed Fuel Consumption

1	**Condition**	3 ≥ GR ≥ -3
	Equation	CSFC = (1618.8 - 864.83*LN(AES) + 124.88*(LN(AES))^2 + 32.087*GR) / (1 - 0.16247*LN(AES) - 0.07074*GR + 0.011717*GR^2 - 0.0011606*GR^3)
2	**Condition**	GR < -3
	Equation	CSFC = -305.94 + 76.547*LN(AES) + 2737.7/AES - 5493.1*EXP(-AES)
3	**Condition**	GR > 3
	Equation	CSFC = (1607 - 986.23*LN(AES) + 149.01*(LN(AES))^2 + 84.747*GR) / (1 - 0.17168*LN(AES) - 0.021455*GR)

E.9.2 Constant-Speed Oil Consumption (CSOC)

Table E-81. 5+ Axle Combination Truck Constant-Speed Oil Consumption

1	**Condition**	GR > 0 and AES < 55
	Equation	CSOC=exp(4.60-0.668*ln(AES)-0.01879*GR^2+0.394*GR-0.000873*AES*GR)
2	**Condition**	GR > 0 and AES ≥ 55
	Equation	CSOC=9.383+0.003478*AES-0.271*AES+3.040*GR
3	**Condition**	min(-1.5,-AES/15.0) < GR ≤ 0 and AES < 55
	Equation	CSOC=42.6+0.000189*AES^3-0.0273*AES^2+1.633*AES-18.96*ln(AES)
4	**Condition**	min(-1.5,-AES/15.0) < GR ≤ 0 and AES ≥ 55
	Equation	CSOC=9.383+0.003478*AES^2-0.271*AES
5	**Condition**	GR ≤ min(-1.5,-AES/15.0) and AES < 55
	Equation	CSOC=exp(2.52+0.000397*AES^2-0.0675*AES-0.0353*GR^2-0.652*GR)
6	**Condition**	GR ≤ min(-1.5,-AES/15.0) and AES ≥ 55
	Equation	CSOC=115.8+0.5094*AES-37.27*ln(AES)-3.064*GR

E.9.3 Constant-Speed Tire Wear (CSTW)

Table E-82. 5+ Axle Combination Truck Constant-Speed Tire Wear

1	**Condition**	GR≥2.5 and AES < 55
	Equation	$CSTW=exp(-1.6+0.0000684*AES^2+0.00608*AES+1.567*ln(GR)-0.000762*AES*GR)$
2	**Condition**	GR≥2.5 and AES ≥ 55
	Equation	$CSTW=1.122+0.000357*AES^2-0.03264*AES+0.06295*GR^2+0.005081*AES*GR$
3	**Condition**	(-0.5 < GR < 2.5 and AES<15) or (-AES/35 < GR < 2.5 and AES ≥ 15)
	Equation	$CSTW=0.1432+1.248*10^{-6}*AES^3+0.0639*GR^2+0.1167*GR+0.00332*AES*GR$
4	**Condition**	GR < -AES/35 and AES ≥ max(15.,-25*GR)
	Equation	$CSTW=-0.1283+1.442*10^{-6}*AES^3+0.01044*AES+0.208*GR^2+0.01337*AES*GR$
5	**Condition**	otherwise
	Equation	$CSTW=exp(-3.05-1.5*10^{-6}*AES^3-0.01358*AES+2.13*ln(-GR)-0.001779*AES*GR)$

E.9.4 Constant-Speed Maintenance and Repair (CSMR)

Table E-83. 5+ Axle Combination Truck Constant-Speed Maintenance and Repair

1	**Condition**	GR ≥ 0
	Equation	$CSMR=44.9+0.01148*AES^2+0.254*AES*GR$
2	**Condition**	GR < 0 and AES > 25 and AES ≥ -40*GR-15
	Equation	CSMR = 78.7+1.545*AES-20.6*ln(AES)+0.254*AES*GR
3	**Condition**	otherwise
	Equation	$CSMR=0.996-0.00149*AES^2-15.8*GR$

E.9.5 Constant-Speed Depreciation (CSVD)

Table E-84. 5+ Axle Combination Truck Constant-Speed Vehicle Depreciation

1	**Condition**	AES < 55
	Equation	CSVD = 0.395+0.001215*AES-0.0941*ln(AES)
2	**Condition**	otherwise
	Equation	CSVD = 0.05657+1.598/AES

E.9.6 Excess Fuel Consumption Due to Speed Variability (SCCFC)

Table E-85. 5+ Axle Combination Truck Excess Fuel Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCFC=0.3584*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCFC=2.052+1.167*CSMAX+0.03292*CSMAX^2$

E.9.7 Excess Oil Consumption Due to Speed Variability (SCCOC)

Table E-86. 5+ Axle Combination Truck Excess Oil Consumption Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCOC=0.0028*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCOC=exp(-3.735+0.6849*ln(CSMAX)+0.000112*CSMAX^2)$

E.9.8 Excess Tire Wear Due to Speed Variability (SCCTW)

Table E-87. 5+ Axle Combination Truck Excess Tire Wear Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCTW=0.0012*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	$SCCTW=exp(-6.643+1.947*ln(CSMAX)-721*10^{-7}*CSMAX^2)$

E.9.9 Excess Maintenance and Repair Due to Speed Variability (SCCMR)

Table E-88. 5+ Axle Combination Truck Excess Maintenance and Repair Due to Speed Variability

1	**Condition**	CSMAX < 5
	Equation	$SCCMR=0.0012*CSMAX^2$
2	**Condition**	$CSMAX \geq 5$
	Equation	SCCMR=exp(-6.705+0.008136*CSMAX+1.94*ln(CSMAX))

E.9.10 Excess Depreciation Due to Speed Variability (SCCD)

Table E-89. 5+ Axle Combination Truck Excess Depreciation Due to Speed Variability

1	**Condition**	$CSMAX < 60$
	Equation	$SCCD=0.0002*CSMAX$
2	**Condition**	$CSMAX \geq 60$
	Equation	$SCCD=exp(-5.007+0.000162*CSMAX^2)$

E.9.11 Excess Fuel Consumption Due to Curves (CFC)

Table E-90. 5+ Axle Combination Unit Truck Excess Fuel Consumption Due to Curves

1	**Condition**	$DCA < 6$ and $AES \leq 20$
	Equation	$CFC = MAX(0, EXP(4.892 - 5.8015/DCA^2 - 0.070341*AES - 6.612/AES^{(0.5)}))$
2	**Condition**	$20 < AES \leq (64 + 0.93749*DCA - 13.928 * DCA^{(0.5)})$ and $DCA < 6$
	Equation	$CFC = MAX(0, -0.76579 + 9.3637*LN(DCA) + 0.025171*AES - 0.75491*(LN(DCA))^2 + 0.00010068*AES^2 - 0.22116*AES*LN(DCA))$
3	**Condition**	$AES \leq (64 + 0.93749*DCA - 13.928 * DCA^{(0.5)})$ and $DCA \geq 6$
	Equation	$CFC = MAX(0, -44.672 + 15.308*LN(DCA) + 31.804*LN(AES) - 1.8472*(LN(DCA))^2 - 5.3075*(LN(AES))^2 - 3.5085*LN(DCA)*LN(AES))$
4	**Condition**	$DCA > 1$ and $AES \geq (67 + 0.93749*DCA - 13.928 * DCA^{(0.5)})$
	Equation	$CFC = MAX(0, EXP(-37.185 - 0.0034062*DCA^2 + 1.262*(LN(DCA))^2 - 0.00000046205*AES^3 + 8.9915*LN(AES)))$
5	**Condition**	$DCA \leq 1$ and $AES \geq (67 + 0.93749*DCA - 13.928 * DCA^{(0.5)})$
	Equation	$CFC = MAX(0, -3.3518 + 58.52/((1 + ((DCA - 3.8448)/3.142)^2) * (1+ ((AES - 99.792)/14.486)^2)))$
6	**Condition**	Otherwise
	Equation	$CFC = 0$

E.9.12 Excess Tire Wear Due to Curves (CTW)

Table E-91. 5+ Axle Combination Unit Truck Excess Tire Wear Due to Curves

1	**Condition**	(DCA ≥ 16 and AES ≥ (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (16 > DCA ≥ 6 and AES ≥ (35 - 125/DCA + 750/DCA^2)) or (1 ≤ DCA < 6 and AES ≥ (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3))
	Equation	CTW = MAX(0, EXP(-40.193 + 14.371*EXP(DCA/-53.803) + 1.2303*(LN(DCA))^2 - 1.8886*AES/LN(AES) + 7.0737*AES$^{(0.5)}$))
2	**Condition**	DCA < 1 and AES ≥ (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3)
	Equation	CTW = MAX(0, 1/(1.1442 - 0.015388*DCA^3 - 9704.3/AES$^{(1.5)}$ + 27917*LN(AES)/AES^2 - 42372/AES^2))
3	**Condition**	(DCA ≥ 16 and AES < (0.02381*DCA^2 - 1.4524*DCA + 42.143)) or (16 > DCA ≥ 6 and AES < (35 - 125/DCA + 750/DCA^2))
	Equation	CTW = MAX(0, -27.686 + 18.235*LN(DCA) + 24.103*LN(AES) - 2.2305*(LN(DCA))^2 - 4.3932*(LN(AES))^2 - 4.4593*LN(DCA)*LN(AES))
4	**Condition**	DCA < 6 and AES < (23.334 + 112.5/DCA - 150.83/DCA^2 + 25/DCA^3)
	Equation	CTW = MAX(0, -4.9124 + 4.8372*DCA + 0.12051*AES - 0.2845*DCA^2 - 0.0011691*AES^2 - 0.08169*DCA*AES)

E.9.13 Excess Maintenance and Repair Due to Curves

Table E-92. 5+ Axle Combination Unit Truck Excess Maintenance and Repair Due to Curves

1	**Condition**	(DCA ≥ 10 and AES ≥ (-0.5*DCA + 32.5)) or (10 > DCA ≥ 3 and AES ≥ (-2.8571*DCA + 56.071)) or (DCA < 3 and AES ≥ (6.6667*DCA + 27.5)
	Equation	CMR = EXP(703.2 + 0.75135*(LN(DCA))^2 - 1.3433/DCA$^{(0.5)}$ - 62.464*LN(AES) - 2045.3/LN(AES) + 3128.1/AES))
2	**Condition**	(1.5 ≤ DCA ≤ 3 and (5*DCA + 22.5) > AES > (-5*DCA + 17.5)) or (16 ≤ DCA ≤ 25 and AES ≤ 17.5) or (DCA > 25 and AES <= (-1*DCA + 42.5)) or (3 < DCA < 16 and AES ≤ (-1.5385*DCA + 42.115))
	Equation	CMR = 0.1
3*	**Condition**	(2.5 < DCA ≤ 6.5 and 12.5 ≤ AES ≤ 27.5) or (3.5 < DCA ≤ 10.5 and 7.5 ≤ AES < 22.5) or (9.5 ≤ DCA ≤ 15 and 2.5 < AES ≤ 17.5) or (15 ≤ DCA ≤ 17 and 7.5 ≤ AES ≤ 17.5) or (17 ≤ DCA < 22.5 and 7.5 ≤ AES ≤ 12.5)
	Equation	CMR = CMR + 0.1
4*	**Condition**	(3.5 < DCA < 6.5 and 17.5 ≤ AES < 22.5) or (4.5 < DCA < 10.5 and 12.5 ≤ AES ≤ 17.5) or (7.5 < DCA < 10.5 and 7.5 < AES ≤ 12.5)
	Equation	CMR = CMR + 0.1
5	**Condition**	Otherwise
	Equation	CMR = 0

* The third and fourth equations for 5+ Axle Combination Unit Truck excess maintenance and repair due to curves are, under certain conditions, used to increment the CMR value derived from the second equation. These conditions for one or both of these equations may be true when the condition for equation two is true.

E.10 Pavement Condition Adjustment Factors

Pavement condition affects the 5 constant-speed operating cost consumption categories.

E.10.1 Constant-Speed Fuel and Oil Consumption (PCAFOC)

Table E-93. Fuel and Oil Consumption Pavement Condition Adjustment Factors

1	**4-Tire Vehicles**	PCAFOC = 2.64+0.0729*PSR^2-0.722*PSR
2	**Trucks**	PCAFOC = 1.176-0.1348*ln(PSR)

E.10.2 Constant-Speed Tire Wear (PCAFTW)

Table E-94. Tire Wear Pavement Adjustment Factors

1	**4-Tire Vehicles**	PCAFTW = 2.40-1.111*ln(PSR)
2	**Trucks**	PCAFTW = 1.668+0.001372*PSR^{3}-0.581*ln(PSR)

E.10.3 Constant-Speed Maintenance and Repair (PCAFMR)

Table E-95. Maintenance and Repair Pavement Adjustment Factors

	4-Tire Vehicles	PCAFMR = 3.19+0.0967*PSR^{2}-0.961*PSR
	Single-Unit Trucks	PCAFMR = 1.724+0.00830*PSR^{2}-0.661*ln(PSR)
	Combination Trucks	PCAFMR = 2.075+0.273*PSR-1.622*ln(PSR)

E.10.4 Constant-Speed Depreciation (PCAFVD)

Table E-96. Vehicle Depreciation Pavement Adjustment Factors

	4-Tire Vehicles	PCAFVD = 1.136-0.106*ln(PSR)
	Single-Unit Trucks	PCAFVD = 1.332-0.262*ln(PSR)
	Combination Trucks	PCAFVD = 1.32-0.254*ln(PSR)

Appendix F:

Procedures for Estimating Air Pollution Costs

F.1 Overview

HERS calculates the monetary value of damages from air pollution generated by motor vehicles using a sample section under "baseline" conditions during each funding period, and with each candidate improvement to that sample section. Air pollution costs under baseline or improved travel conditions on a section depend upon three factors: (1) HERS' estimates of average daily traffic volume on the section during each funding period; (2) the mix of vehicle classes that typically use facilities of the type represented by the sample section; and (3) HERS' estimates of the average effective speed (AES) of travel on the section during each future funding period. Figure F-1 illustrates the process used to calculate air pollution costs for a sample section under each set of travel conditions.[1]

Differences in air pollution costs between baseline or unimproved travel conditions – including daily traffic volume and average effective speed – and conditions with an improvement in place are included in HERS' calculation of the net benefits from implementing that improvement. Reductions in air pollution costs *increase* the net benefits from an improvement, while an increase in the air pollution costs generated by the travel volume and speed estimated to result from an improvement *reduce* its net benefits. Changes in air pollution costs resulting from an improvement's effect on travel conditions on a sample section increase or reduce the benefits from making that improvement during all funding periods comprising its lifetime.

F.1.1 How Improvements Affect Air Pollution Costs

Differences between baseline travel conditions and conditions with an improvement in place can cause total air pollutant emissions from vehicles traveling on a section to change for two reasons. First, the per-mile *rates* at which motor vehicles emit some pollutants vary with travel speed, and can rise or decline in response to the increase in average speed on a sample section that results from an improvement. Second, average daily traffic and thus total vehicle-miles of travel on a section increases from its baseline level under improved conditions due to the response of travel demand to the increase in average travel speed on the section.

By increasing the volume of travel on a section, a candidate improvement increases air pollutant emissions and their resulting costs, since these costs are assumed to

1. The broad outline for these procedures was developed by Apogee Research under contract to the Federal Highway Administration, and is documented in the report *Procedures for Incorporating Air Pollution Effects in the HERS Model for National Highway Investment Analysis*, September 1996.

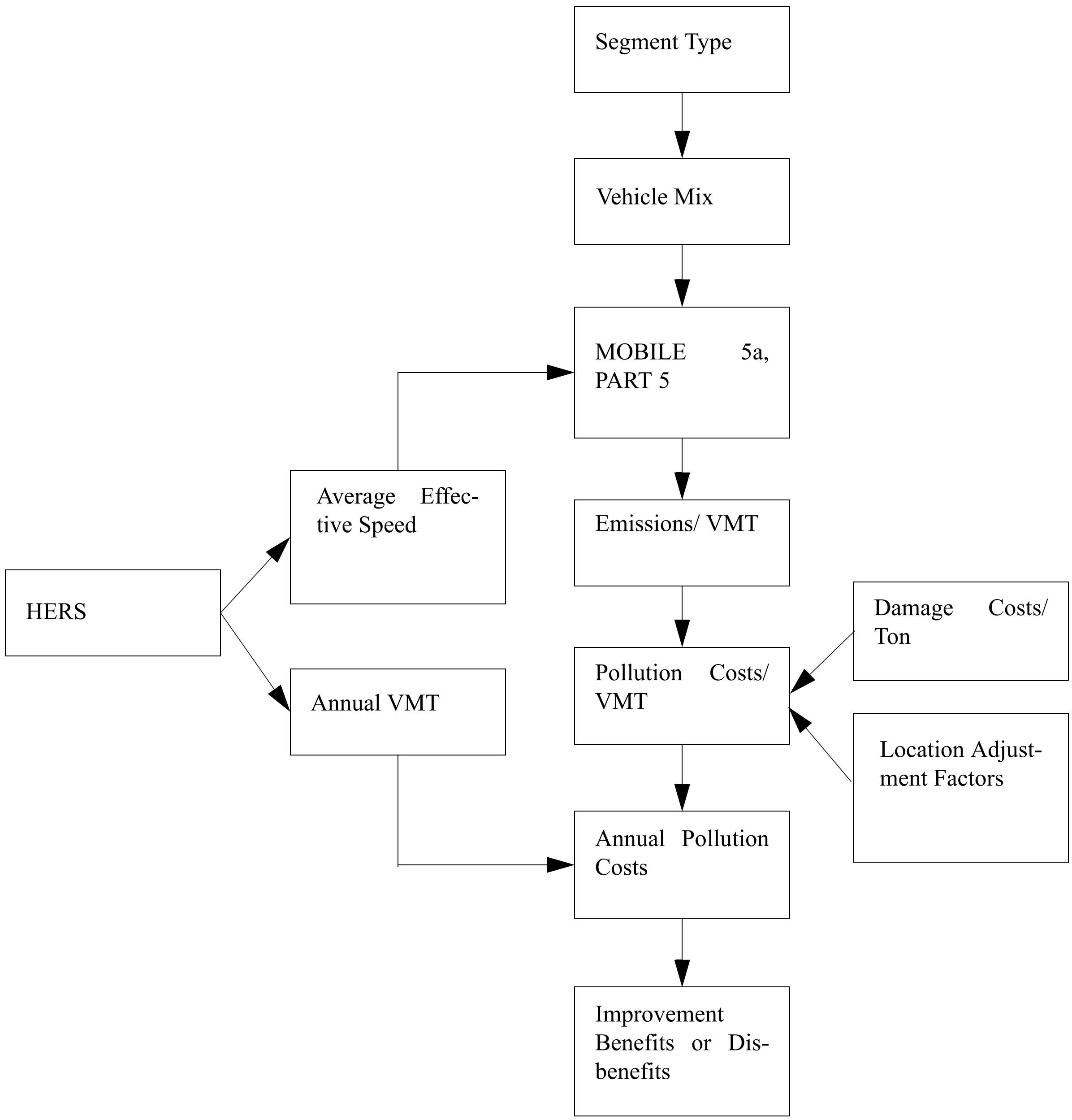

Figure F-1. Overview of HERS Procedure for Estimating Air Pollution Costs

depend directly on total emissions. At the same time, the increase in average travel speed on the segment can reduce emissions per *vehicle-mile* of some pollutants, thus offsetting some or all of the effect of higher travel volumes on total air pollution costs. However, particularly large speed increases can actually cause per-mile emission rates of some pollutants to rise, thereby "magnifying" the increase in air pollution costs from higher travel volumes. Thus total air pollution costs resulting from travel on a HERS sample section can either rise or fall as the result of an improvement.

F.1.2 Critical Assumptions

Differences in air pollutant emissions generated by changes between baseline and improved travel conditions are assumed to contribute directly to changes in atmospheric concentrations of those pollutants. In turn, the total costs of damages to human health and property from air pollution are assumed to vary in response to changes in these atmospheric concentrations. Thus potential improvements to a HERS sample section are assumed to alter total air pollution damage costs in exact proportion to any change in pollutant emissions generated by vehicles traveling on the section that results from an improvement. HERS uses widely-accepted estimates of the dollar value of health and property damages caused per ton of each major pollutant to calculate air pollution costs from travel on sample sections under baseline and improved conditions.

Because the air pollution cost estimates used by HERS represent nationwide averages for dollar damages to human health and property caused by individual pollutants, they reflect the exposure of residents and property to air pollution that occurs at typical U.S. population and development densities. For pollutants that tend to remain concentrated near their original source, HERS scales these average per-ton damage costs upward to reflect the greater population and property exposure to emissions of those pollutants from vehicles using sample sections located in urban areas. Conversely, HERS scales these nationwide average damage costs downward to reflect the lower population and development densities that typically surround sample sections located outside urban areas. For pollutants that tend to disperse widely, HERS applies nationwide average damage costs per ton of emissions generated by travel on both urban and non-urban sample sections.

HERS estimates the changes in costs from air pollution damages that would result from all candidate improvements to a sample section during the current and each future funding period. Because the per-mile rates at which motor vehicles emit most air pollutants are expected to decline throughout the time horizon considered by HERS, air pollution costs on most sample sections are expected to fall throughout the foreseeable future under both baseline and improved travel conditions. As a result, differences in air pollution costs between baseline and improved conditions – and thus the *changes* in air pollution costs that HERS includes among the benefits or disbenefits resulting from candidate improvements – are expected to decline during each successive future funding period considered by the model.

F.2 Estimating Air Pollutant Emissions

F.2.1 Specific Pollutants Considered

Motor vehicles' contribution to air pollution consists partly of tailpipe emissions of four commonplace pollutants that can accumulate in unhealthful concentrations in the earth's atmosphere: carbon monoxide (usually abbreviated CO), sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter less than 2.5 microns in diameter (PM2.5). Under certain conditions, nitrogen oxides also combine in the atmosphere with other chemical compounds emitted by motor vehicles (among other sources) to form ground-level ozone.[2] Atmospheric levels of airborne dust, another pollutant

2. These "volatile organic compounds" (VOC) are emitted from the tailpipes of gasoline-powered vehicles, as well as by the evaporation of gasoline during vehicle refueling, storage, and operation.

that can be harmful to human health and property when it reaches certain concentrations, are also increased as moving vehicles' tires contact road pavement surfaces.

F.2.2 Emission Rates for HERS Vehicle Classes and Section Types

Different types of motor vehicles emit each of these six pollutants at varying rates per mile of travel. Vehicles' emission rates depend on the type of fuel used (gasoline or diesel), engine size, and vehicle weight, as well as on operating conditions such as ambient temperature, road grade, and altitude. Emission rates for some pollutants - principally carbon monoxide, volatile organic compounds, and nitrogen oxides – also vary with vehicles' average operating speeds, while others (sulfur oxides, particulate matter, and road dust) are approximately constant regardless of speed. In addition, emission rates for individual vehicle classes can vary among different roadway types even for travel at the same average speed, because the characteristic patterns of acceleration, braking, and cruising that produce a given average speed differ among major roadway classes, such as freeways, arterials, and collectors.

Each of the nine section types utilized by HERS, which are differentiated by location (urban vs. rural) and functional class (expressway, arterial, collector) tends to be used by a characteristic mix of vehicle types. Differing vehicle mixes reflect the varying combinations of travel purposes served by different road and highway facilities, together with the common use of specific types of vehicles to provide different types of transportation services. Table F-1 reports the characteristic distribution of total vehicle-miles traveled among the seven detailed vehicle classes employed by HERS for each of its nine different roadway section types.

Emission rates for each HERS vehicle class operating on different types of roadways were first estimated for the various pollutants using models developed by the U.S. Environmental Protection Agency (EPA). These rates measure average emissions per vehicle-mile of travel on freeway, arterial, and collector sections for each of the six air pollutants whose damage costs are considered by HERS. The MOBILE6 motor vehicle emission factor model was used to estimate average emissions per vehicle-mile of travel at different average speeds for carbon monoxide (CO), volatile organic compounds (VOCs), and oxides of nitrogen (NOx) as functions of average travel speed and roadway type.[3] The EPA's vehicle emission factor model for particulate pollutants, PART5, was used to estimate average emissions per vehicle-mile of sulfur oxides (SOx), small particulate matter (PM-10), and road dust generated by individual vehicle classes operating on each HERS section type.[4] Emissions of these pollutants are assumed by PART5 to be independent of vehicle operating speeds. Both emission models' "default" assumptions regarding the age distribution of the U.S. vehicle fleet and operating conditions such as typical fuel composition, ambient temperatures, and altitude were employed in developing these estimates.

Developing these emission rates required detailed "mapping" of the distribution of vehicle travel among the seven detailed vehicle classes employed by HERS into the different vehicle classification systems employed by MOBILE6 (which employs 16 separate vehicle types) and PART5 (12 vehicle types). This was accomplished using extremely detailed data on travel by vehicle type, weight, and roadway class derived

3. For a brief description of the structure of the MOBILE model, see The MOBILE Model and Transportation Planning, Report FHWA-PD-96-005, Federal Highway Administration, September 1995. Complete documentation of MOBILE is available at http://www.epa.gov/otaq/m6.htm
4. The PART5 model is described in An Overview of PM-10 Base Year Emission Inventories, Report FHWA-PD-98-002, Federal Highway Administration, November 1997.

Table F-1. Distribution of Travel Among HERS Vehicle Classes by Section Type

Section Type	Four Tire Vehicles				Single Unit Trucks			Combination Trucks		
	Small Autos	Med/Lg Autos	Pickups & Vans	All Four Tire Vehicles	Six-Tire Trucks	3 + Axle SUTs	All Single Unit Trucks	3 - 4 Axles	5 or More Axles	All Combination Trucks
Rural Interstate	28.4%	34.2%	37.3%	100.0%	83.9%	16.1%	100.0%	7.4%	92.6%	100.0%
Rural OPA*	26.9%	32.4%	40.8%	100.0%	79.6%	20.4%	100.0%	9.4%	90.6%	100.0%
Rural Minor Arterial	26.7%	32.2%	41.1%	100.0%	79.2%	20.8%	100.0%	11.7%	88.3%	100.0%
Rural Major Collector	25.7%	31.0%	43.3%	100.0%	77.5%	22.5%	100.0%	12.3%	87.7%	100.0%
Urban Interstate	30.4%	36.9%	32.7%	100.0%	81.5%	18.5%	100.0%	9.2%	90.8%	100.0%
Urban Other Fwy/ Exwy	31.4%	38.1%	30.5%	100.0%	82.1%	17.9%	100.0%	12.4%	87.6%	100.0%
Urban OPA*	29.5%	35.7%	34.7%	100.0%	80.8%	19.2%	100.0%	16.6%	83.4%	100.0%
Urban Minor Arterial	30.1%	36.4%	33.6%	100.0%	73.5%	26.5%	100.0%	26.5%	73.5%	100.0%

OPA indicates Other Principal Arterials.

Source: Estimated by Volpe Center from 1999 HPMS data on VMT by vehicle type and functional class supplied by FHWA Office of Highway Policy Information.

from the HPMS system, which were provided by FHWA's Office of Highway Policy Information. These data were employed as an intermediate or "translating" stage between the vehicle classification systems used by HERS and each of the two emission factor models, in conjunction with detailed descriptions of the weight ranges and physical characteristics of vehicles used by HERS, MOBILE6, and PART5 to classify vehicles. Table F-2 and Table F-3 show the relationships between HERS' seven detailed vehicle classes and the vehicle classes employed by the MOBILE6 and PART5 emission factor models.

For the three speed-sensitive pollutants, emission rates for each of the seven detailed vehicle classes and nine section types employed by HERS were estimated at speeds ranging from 5 to 70 mph in 5-mph increments. The measure used by the MOBILE6 emissions factor model to adjust individual vehicle types' emission rates for speed variation represents the average operating speeds for several different "driving cycles" that combine different phases of vehicle operation (acceleration, cruising, braking, and idling) in varying proportions.[5] The specific driving cycles used to test variation in different vehicle classes' emission rates are intended to represent typical trips that specific types of vehicles are commonly used to make, and that result in different overall average speeds. This measure of travel speed is broadly consistent with the average effective speed (AES) measure employed by HERS, which is intended to represent the average speed of travel on a section associated with its predicted daily

5. Emissions for a sample of vehicles are measured on each of these driving cycles, and expressed relative to those measured for the test cycle used to certify their compliance with prevailing federal emission standards. The resulting "speed correction factors" are used to estimate vehicles' emissions when driven at speeds other than the approximately 20 mph average of the certification test cycle.

Table F-2. Relationship of MOBILE6 Vehicle Classes to HERS Vehicle Classes

MOBILE6 Vehicle Class	Proportion of MOBILE6 Vehicle Class Included in HERS Vehicle Class:						
	Small Autos	Medium/ Large Autos	Pickups & Vans	Six-Tire Trucks	3+ Axle SUTs	3-4 Axle Combos	5+ Axle Combos
LDGV	0.9991	0.9179					
LDDV	0.0009	0.0008					
LDGT1		0.0813					
LDGT2			0.6835				
LDGT3			0.2142				
LDGT4			0.0984				
LDDT34			0.0040				
HDGV2B				0.8002			
HDDV2B				0.1998			
HDGV3					0.1778		
HDDV3					0.3733		
HDGV4					0.0284		
HDDV4					0.1756		
HDGV5					0.1311		
HDDV5					0.1138		
HDGV6						0.1689	
HDDV6						0.2876	
HDGV7						0.0781	
HDDV7						0.4654	
HDGV8A							0.0001
HDDV8A							0.1606
HDGV8B							0.0000
HDDV8B							0.8393
All Classes	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Source: Estimated by Volpe Center from 1999 HPMS data on VMT by vehicle type and functional class supplied by FHWA Office of Highway Policy Information.

travel volume, assuming a characteristic mix of vehicle classes and distribution of travel between peak and off-peak periods for that section type.

Table F-3. Relationship of PART5 Vehicle Classes to HERS Vehicle Classes.

PART5 Vehicle Class	Proportion of PART5 Vehicle Class Included in HERS Vehicle Class:						
	Small Autos	Medium/ Large Autos	Pickups & Vans	Six-Tire Trucks	3+ Axle SUTs	3-4 Axle Combos	5+ Axle Combos
LDGV	0.9991	0.9991					
LDGT1			0.7303				
LDGT2			0.2571				
HDGV				0.8002	0.3373	0.2470	0.0001
MC							
LDDV	0.0009	0.0009					
LDDT			0.0126				
2BHDDV				0.1998			
LHDDV					0.6627		
MHDDV						0.7530	
HHDDV							0.9999
BUSES							
All Classes	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

F.2.3 Future Trends in Emission Rates

In response to the progressive tightening of federal regulations on new motor vehicles' emission rates, the vehicles added to the U.S. fleet each year are significantly less polluting than those they replace.[6] The downward trend in average emission rates resulting from such "turnover" of the vehicle fleet is reflected in the estimates of future emission rates for individual vehicle classes produced by the MOBILE6 and PART5 models.[7] Thus the average emissions rates by vehicle class and speed for each pollutant and section type calculated by HERS will reflect this projected downward trend in future emission rates.

As a consequence, estimated air pollution costs under baseline and improved travel conditions on each sample section are predicted to decline over successive future funding periods. HERS' estimates of differences in air pollution costs between baseline and improved travel conditions on each section — which the model includes in its estimates of the benefits from potential improvements to the section – are also expected to narrow during each successive future funding period considered by HERS. Thus the effect of considering air pollution costs on the likelihood that HERS will select candidate improvements to a sample section also diminishes during each successive future funding period.

F.2.4 Final Emission Rates

This process produced a set of tables showing emissions of a single pollutant per vehicle-mile of travel at different average speeds by each of HERS' seven detailed vehicle classes, for one of its nine roadway section types. Table F-4 provides one example: it shows average carbon monoxide emissions (in grams per vehicle-mile traveled) at speeds from 5 to 50 mph for each of HERS' seven detailed vehicle classes operating on Rural Major Arterials, one of HERS' nine roadway section types, for the year 2000. In order to ensure that the projected decline in future emission rates is accurately reflected in the estimates of future air pollution damage costs – and in HERS' estimates of benefits or disbenefits from improvements proposed during future years – emission rates for each pollutant, vehicle class, and section type were also estimated for the year 2015. This represents approximately the outer time horizon recommended for use with the MOBILE6 and PART5 emissions models.

Average emissions rates for each pollutant and HERS vehicle class differ among the nine section types even at the same average speed, partly because the representation of the 16 different MOBILE6 vehicle classes and the 12 PART5 vehicle classes in each HERS vehicle class differs very slightly among section types. In addition, the typical driving cycles and resulting emissions rates that are associated with the same average speed differ among roadway types. For three of the six pollutants – carbon

6. The effect on average emissions of adding new, cleaner vehicles to the fleet has been partly offset by the tendency for aging vehicles - most of which met less stringent emission standards when new – to be kept in service for longer periods and to be used more intensively than has historically been the case. Shifts toward heavier vehicles that are subject to less stringent emission standard, particularly the increasing substitution of light trucks (pickups, vans, and sport/utility vehicles) for automobiles as passenger vehicles, have also offset some of the effect of new vehicles' progressively lower emission rates. On balance, however, individual vehicle classes' and fleet-wide average emission rates for most pollutants have declined significantly in recent years, and are expected to decline significantly over the foreseeable future.
7. Both models also assume continued increases in the number of light- duty trucks used as passenger vehicles and in the average weight of heavy-duty trucks over the future, which slightly slow the decline in fleet-wide average emissions rates resulting from a progressively "cleaner" fleet.

Table F-4. Carbon Monoxide (CO) Emission Rates by HERS Vehicle Class for Urban Other Principal Arterials (grams/mile)

Speed (mph)	HERS Vehicle Class:						
	Small Autos	Medium/ Large Autos	Pickups & Vans	Six-Tire Trucks	3+ Axle SUTs	3-4 Axle Combos	5+ Axle Combos
5	41.82	41.70	56.11	71.74	71.89	59.90	20.94
10	29.02	28.77	38.87	47.79	47.90	40.01	14.44
15	25.62	25.33	34.35	33.60	33.71	28.21	10.42
20	23.93	23.62	32.08	24.96	25.05	20.99	7.87
25	23.02	22.70	30.87	19.58	19.66	16.48	6.22
30	22.62	22.29	30.29	16.24	16.30	13.66	5.14
35	22.73	22.40	30.37	14.22	14.27	11.95	4.45
40	23.57	23.25	31.36	13.16	13.19	11.03	4.03
45	24.42	24.11	32.35	12.86	12.88	10.75	3.83
50	25.27	24.97	33.34	13.28	13.29	11.06	3.80
55	26.11	25.82	34.32	14.48	14.47	12.01	3.94
60	26.96	26.68	35.31	16.70	16.66	13.75	4.29
65	27.80	27.52	36.30	20.33	20.24	16.66	4.88

Source: estimated by Volpe Center using Table 2 and EPA MOBILE6 motor vehicle emission factor model.

monoxide, volatile organic compounds, and nitrogen oxides – average emissions rates by individual HERS vehicle classes on each section type vary in response to changes in the average effective speed of travel. Thus the emission rates calculated by HERS for these three pollutants will differ between baseline conditions and those with each candidate improvement in place. In contrast, average emission rates for the three remaining pollutants – sulfur oxides, particulate matter, and road dust – do not vary significantly with travel speed, and will thus be identical under baseline and improved conditions within a funding period. Finally, average emission rates for all six pollutants generated by all vehicle classes on all section types will decline across the entire range of travel speeds during future years.

F.3 Air Pollution Damage Costs

F.3.1 Damage Costs for Individual Air Pollutants

The estimated costs of human health and property damage per ton of each pollutant that are employed in HERS were derived from a widely cited recent study.[8] These values are derived by dividing the study's estimate of total annual costs from health and property damages caused by highway vehicles' contribution to atmospheric levels of each individual pollutant by the total number of tons of that pollutant emitted annually by highway vehicles. Thus they represent estimates of nationwide average damage costs per ton of each pollutant, given the typical atmospheric levels of those pollutants that prevailed at the time the study was conducted (1995). These values are assumed to represent acceptable estimates of the changes in total health and property damage costs that would result if emissions of each pollutant changed by one ton. HERS provides the option of using either the midpoint or the upper limit of the range

8. McCubbin, D. and M. Delucchi. Health Effects of Motor Vehicle Air Pollution. Institute for Transportation Studies, University of California, Davis, 1996.

for costs per ton of each pollutant implied by the study's reported range of estimates for total annual economic costs attributable to each pollutant. These dollar-denominated damage costs per ton of each pollutant are assumed to remain constant over all future funding periods considered by HERS.

F.3.2 Adjustments to Per-Ton Damage Costs

The cost per ton estimates derived from this study represent average damage costs from exposure to prevailing air pollution levels that occurs at typical U.S. population and development densities. For pollutants that remain concentrated near their original sources, these average costs should be scaled up or down to reflect local variation in damage costs resulting from differences in population and property exposure to air pollution caused by higher or lower population and development density surrounding those sources. Unfortunately, however, usable information on the location of each sample sections is limited to whether it is located within an urbanized area or not; in the absence of more detailed data, HERS uses each sample section's urban or non-urban location to adjust the nationwide average costs per ton of each individual pollutant generated by vehicles traveling on it.

Specifically, HERS scales costs for the three pollutants that tend to remain localized (carbon monoxide, particulate matter, and road dust) downward from their national average values for sections located outside urbanized areas to reflect the lower density of rural populations located adjacent to highways and thus exposed to these pollutants. Damage costs per ton of these three pollutants emitted by vehicles using sample sections located in urban areas are assumed to equal their nationwide average values. In contrast, average damage costs for the three more widely dispersed pollutants - ozone, nitrogen oxides, and sulfur oxides – are scaled upward from their national averages for sample sections within urbanized areas in order to reflect the larger populations exposed to them. The scaling factors used in this process were developed by examining county-level population and population density data for the 100 largest U.S. metropolitan areas and comparing them to corresponding figures for all non-urbanized counties in the nation. Table F-5 summarizes the moderate and high estimates of per-ton damage costs for each pollutant, as well as the factors used by HERS to make these locational adjustments.

Table F-5. Air Pollutant Damage Costs and Adjustment Factors Used in HERS (2000 $)

Pollutant	Damage Costs ($/ton)	Adjustment Factor:	
		Urban	Rural
Carbon Monoxide	$100	1.0	0.5
Volatile Organic Compounds	$2,750	1.5	1.0
Nirtogen Oxides	$3,625	1.5	1.0
Sulfur Dioxide	$8,400	1.5	1.0
Fine Particulate Matter (PM2.5)	$4,825	1.0	0.5
Road Dust	$4,825	1.0	0.5

Sources: McCubbin and DeLucchi, 1995, and Volpe Center analysis of county population density data from U.S. Census Bureau, 2000 Census of the United States.

F.3.3 Air Pollution Costs per Vehicle-Mile

These damage costs per ton of each pollutant were multiplied by the previously-developed estimates of emissions per mile by vehicle class and speed for each HERS section type during the year 2000, with the per-ton damage cost for each pollutant adjusted appropriately to reflect its urban or rural location. The resulting values for each of the six pollutants were then summed to determine total air pollution damage costs per vehicle-mile of travel for each roadway type and location, vehicle class, and average speed at 5-mph intervals. Damage costs for 1-mph increments were interpolated from the surrounding values for 5-mph increments.

Values for the seven detailed vehicle classes used by HERS were then consolidated to the three aggregate vehicle classes for which the HPMS data records for individual sample sections provide estimated shares of travel (Four-Tire Vehicles, Single-Unit Trucks, and Combination Trucks), using the distributions of the seven detailed vehicle classes within each of these three broader classes on individual roadway types (reported previously in Table _-1); Table _-6 provides an example of the resulting values. Finally, this entire process was repeated for the year 2015, and annual rates of decline in emissions damage costs were estimated from their 2000 and 2015 values for each combination of vehicle class and roadway type. The annual percentage rates at which emission costs decline were assumed to be constant throughout this period (and beyond).

F.3.4 Assessing the Effect of Proposed Improvements on Air Pollution Costs

HERS calculates the economic costs of air pollution generated by annual travel on a sample section by multiplying its estimates of total annual vehicle-miles traveled by each vehicle class (Four-Tire Vehicles, Single-Unit Trucks, and Combination Trucks) by the value of air pollution damage costs per vehicle-mile for the appropriate vehicle class, roadway section type, average travel speed, and calendar year. Air pollution costs per vehicle-mile for the calendar year in which a proposed improvement is being evaluated are calculated by applying the average annual rate of decline over the appropriate number of years to the year-2000 cost estimates.

By repeating this procedure under the baseline and hypothetically improved travel conditions, HERS calculates the change in total air pollution costs generated by travel on the section that would result from implementing each proposed improvement. The change or difference in total air pollution costs between baseline and improved conditions increases or reduces net benefits from the improvement under consideration, depending on whether the changes in average effective speed and annual travel volume by each vehicle class resulting from that improvement cause air pollution costs to rise or decline. This process is repeated to evaluate the effect on net benefits from the candidate improvement from including air pollution costs during each future year making up the expected lifetime of that improvement. HERS then applies the usual process of discounting the stream of future net benefits from each candidate improvement – including its effect on air pollution costs – to its present value in order to evaluate the desirability of selecting that improvement during the current funding period.

F.3.5 Likely Effects of Including Air Pollution Costs

As indicated previously, proposed improvements to a sample section tend to increase air pollution costs by making travel on it less costly and thus raising the level of travel on the section. Thus if air pollutant emissions per vehicle-mile were unaffected by the changes in travel conditions that occur when sample sections are improved, air pollution costs would normally rise, thereby reducing the net benefits from typical improvements. At the same time, however, increases in the average effective speed of travel that result from an improvement can reduce average emissions per vehicle-mile for certain pollutants. By doing so, an improvement can thus reduce average air pollution costs per vehicle-mile traveled on the section, thereby offsetting some or all of the effect of higher travel volumes on total air pollution costs.

As Tables F-6 through F-14 suggests, per-mile air pollution costs on most facility types fall significantly as speeds increase up to about 40 mph, so benefits from improvements that increase speeds over this range are likely to be reduced only modestly - and may actually be increased in some cases – by including air pollution costs. Because per-mile emission rates and thus air pollution costs for most vehicle classes and roadway types begin to rise gradually above about 40 mph, however, large speed increases resulting from an improvement can accentuate the increase in air pollution costs caused by higher travel volumes.

Thus where travel speeds on sample sections under baseline or unimproved conditions are already above about 40 mph, the increase in air pollution costs resulting from the higher travel volumes produced by most improvements will be reinforced by an increase in per-mile air pollution costs. This same effect may also occur where baseline travel speeds are below the 45 mph threshold, but where candidate improvements to a sample section produce very large increases in travel speeds. In these cases, including air pollution costs may significantly reduce the net benefits from many potential improvements considered by HERS, making them less likely to be selected.

Air pollution damage costs per vehicle-mile differ considerably among the various section types considered by HERS across the entire range of travel speeds. Air pollution costs imposed by travel on facilities located in urban areas are significantly higher than those for identical facility types in rural areas because of the increased exposure to air pollution experienced by residents and properties surrounding sample sections located in urbanized areas. Average costs per vehicle-mile are also higher for facilities that carry larger shares of heavy vehicle travel (Interstate highways and other major arterials), since the per-mile rates at which trucks and other heavy vehicles emit some pollutants are much higher than those for light-duty vehicles. Thus considering air pollution costs is more likely to result in significant reductions in net benefits from candidate improvements to higher-order facilities (Interstate highways and other major arterials) and sample sections in urbanized locations.

On balance, the increase in air pollution costs from higher travel volumes seems likely to outweigh the effect of any decline in per-mile pollution costs for most proposed improvements. Thus considering air pollution costs will make most improvements slightly less likely to meet the benefit-cost criterion used by HERS to select improvements for adoption. Across the very large number of sample sections analyzed by HERS, the result seems likely to be a reduction in the number and value of improvement projects that are selected by HERS when the economic efficiency criterion is employed. Where projects are selected on a different basis, including air pollution costs is likely to reduce the net benefits generated by any selected set of improvements.

Table F-6. Emission Damage Costs by HERS Vehicle Class: Rural Interstate[a]

Speed	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.03283	$0.05347	$0.14932
6	$0.02902	$0.04925	$0.14350
7	$0.02630	$0.04623	$0.13935
8	$0.02426	$0.04397	$0.13623
9	$0.02267	$0.04221	$0.13380
10	$0.02140	$0.04081	$0.13186
11	$0.02031	$0.03930	$0.12864
12	$0.01940	$0.03805	$0.12595
13	$0.01863	$0.03699	$0.12368
14	$0.01797	$0.03608	$0.12173
15	$0.01740	$0.03529	$0.12004
16	$0.01708	$0.03448	$0.11805
17	$0.01680	$0.03376	$0.11630
18	$0.01655	$0.03312	$0.11474
19	$0.01633	$0.03255	$0.11334
20	$0.01613	$0.03204	$0.11209
21	$0.01576	$0.03162	$0.11088
22	$0.01543	$0.03125	$0.10978
23	$0.01512	$0.03091	$0.10877
24	$0.01484	$0.03060	$0.10785
25	$0.01459	$0.03031	$0.10701
26	$0.01477	$0.03010	$0.10636
27	$0.01493	$0.02991	$0.10575
28	$0.01509	$0.02973	$0.10520
29	$0.01523	$0.02956	$0.10468
30	$0.01537	$0.02941	$0.10419
31	$0.01530	$0.02933	$0.10400
32	$0.01523	$0.02926	$0.10381
33	$0.01517	$0.02919	$0.10364
34	$0.01511	$0.02913	$0.10348
35	$0.01506	$0.02907	$0.10333
36	$0.01506	$0.02909	$0.10355
37	$0.01506	$0.02910	$0.10376
38	$0.01505	$0.02912	$0.10395
39	$0.01505	$0.02914	$0.10414
40	$0.01505	$0.02915	$0.10432
41	$0.01506	$0.02925	$0.10497

Table F-6. Emission Damage Costs by HERS Vehicle Class: Rural Interstate[a]

Speed	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
42	$0.01506	$0.02934	$0.10559
43	$0.01507	$0.02943	$0.10618
44	$0.01507	$0.02951	$0.10674
45	$0.01508	$0.02959	$0.10727
46	$0.01509	$0.02977	$0.10842
47	$0.01510	$0.02994	$0.10951
48	$0.01511	$0.03010	$0.11056
49	$0.01511	$0.03026	$0.11157
50	$0.01512	$0.03041	$0.11254
51	$0.01514	$0.03068	$0.11430
52	$0.01515	$0.03093	$0.11600
53	$0.01516	$0.03117	$0.11763
54	$0.01518	$0.03140	$0.11920
55	$0.01519	$0.03163	$0.12072
56	$0.01521	$0.03200	$0.12332
57	$0.01523	$0.03236	$0.12584
58	$0.01525	$0.03271	$0.12826
59	$0.01527	$0.03304	$0.13061
60	$0.01529	$0.03336	$0.13287
61	$0.01531	$0.03389	$0.13667
62	$0.01533	$0.03439	$0.14034
63	$0.01536	$0.03488	$0.14390
64	$0.01538	$0.03535	$0.14734
65	$0.01540	$0.03581	$0.15068
66	$0.01542	$0.03627	$0.15410
67	$0.01544	$0.03675	$0.15759
68	$0.01546	$0.03722	$0.16116
69	$0.01548	$0.03771	$0.16481
70	$0.01550	$0.03820	$0.16855
r[b]	6.27%	7.79%	12.17%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-7. Emission Damage Costs by HERS Vehicle Class: Rural Other Principal Arterial[a]

Average Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.03584	$0.05605	$0.12750
6	$0.03169	$0.05145	$0.12117
7	$0.02872	$0.04816	$0.11665
8	$0.02649	$0.04570	$0.11326
9	$0.02476	$0.04378	$0.11062
10	$0.02338	$0.04224	$0.10851
11	$0.02228	$0.04059	$0.10504
12	$0.02136	$0.03921	$0.10214
13	$0.02059	$0.03804	$0.09969
14	$0.01993	$0.03704	$0.09759
15	$0.01935	$0.03617	$0.09577
16	$0.01880	$0.03527	$0.09362
17	$0.01831	$0.03448	$0.09172
18	$0.01787	$0.03377	$0.09004
19	$0.01748	$0.03314	$0.08853
20	$0.01713	$0.03257	$0.08717
21	$0.01687	$0.03212	$0.08587
22	$0.01663	$0.03170	$0.08468
23	$0.01641	$0.03132	$0.08360
24	$0.01621	$0.03098	$0.08260
25	$0.01602	$0.03066	$0.08169
26	$0.01586	$0.03042	$0.08099
27	$0.01571	$0.03021	$0.08034
28	$0.01558	$0.03000	$0.07974
29	$0.01545	$0.02982	$0.07917
30	$0.01533	$0.02964	$0.07865
31	$0.01523	$0.02956	$0.07844
32	$0.01514	$0.02948	$0.07824
33	$0.01506	$0.02941	$0.07805
34	$0.01498	$0.02934	$0.07788
35	$0.01490	$0.02927	$0.07771
36	$0.01490	$0.02929	$0.07863
37	$0.01490	$0.02931	$0.07949
38	$0.01489	$0.02933	$0.08030
39	$0.01489	$0.02934	$0.08108
40	$0.01489	$0.02936	$0.08181
41	$0.01489	$0.02947	$0.08185
42	$0.01490	$0.02957	$0.08188
43	$0.01491	$0.02967	$0.08191
44	$0.01492	$0.02977	$0.08194
45	$0.01492	$0.02986	$0.08196
46	$0.01493	$0.03006	$0.08319

Table F-7. Emission Damage Costs by HERS Vehicle Class: Rural Other Principal Arterial[a]

Average Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
47	$0.01494	$0.03025	$0.08437
48	$0.01495	$0.03043	$0.08550
49	$0.01496	$0.03060	$0.08658
50	$0.01497	$0.03077	$0.08762
51	$0.01499	$0.03107	$0.08952
52	$0.01500	$0.03136	$0.09135
53	$0.01502	$0.03163	$0.09311
54	$0.01503	$0.03190	$0.09480
55	$0.01505	$0.03215	$0.09643
56	$0.01507	$0.03258	$0.09924
57	$0.01509	$0.03298	$0.10194
58	$0.01511	$0.03338	$0.10456
59	$0.01513	$0.03376	$0.10708
60	$0.01515	$0.03413	$0.10952
61	$0.01516	$0.03473	$0.11360
62	$0.01517	$0.03530	$0.11755
63	$0.01518	$0.03586	$0.12138
64	$0.01519	$0.03640	$0.12508
65	$0.01520	$0.03693	$0.12868
66	$0.01520	$0.03746	$0.13237
67	$0.01521	$0.03800	$0.13617
68	$0.01522	$0.03855	$0.14008
69	$0.01523	$0.03911	$0.14411
70	$0.01524	$0.03967	$0.14825
r[b]	6.06%	7.79%	11.30%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-8. Emission Damage Costs by HERS Vehicle Class: Rural Minor Arterial[a]

Speed (mph)	Emissions Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.03586	$0.05609	$0.12643
6	$0.03170	$0.05149	$0.12011
7	$0.02873	$0.04820	$0.11560
8	$0.02651	$0.04573	$0.11221
9	$0.02477	$0.04381	$0.10958
10	$0.02339	$0.04228	$0.10747
11	$0.02229	$0.04062	$0.10402
12	$0.02138	$0.03924	$0.10114
13	$0.02060	$0.03807	$0.09871
14	$0.01994	$0.03707	$0.09662
15	$0.01936	$0.03620	$0.09482
16	$0.01881	$0.03530	$0.09268
17	$0.01832	$0.03450	$0.09080
18	$0.01788	$0.03380	$0.08913
19	$0.01749	$0.03317	$0.08763
20	$0.01714	$0.03260	$0.08628
21	$0.01688	$0.03214	$0.08499
22	$0.01664	$0.03172	$0.08381
23	$0.01642	$0.03134	$0.08273
24	$0.01622	$0.03100	$0.08175
25	$0.01603	$0.03068	$0.08084
26	$0.01587	$0.03044	$0.08014
27	$0.01573	$0.03022	$0.07950
28	$0.01559	$0.03002	$0.07890
29	$0.01546	$0.02984	$0.07834
30	$0.01534	$0.02966	$0.07782
31	$0.01524	$0.02958	$0.07761
32	$0.01515	$0.02950	$0.07741
33	$0.01507	$0.02942	$0.07723
34	$0.01499	$0.02936	$0.07705
35	$0.01491	$0.02929	$0.07689
36	$0.01491	$0.02931	$0.07778
37	$0.01491	$0.02933	$0.07862
38	$0.01490	$0.02934	$0.07942
39	$0.01490	$0.02936	$0.08017
40	$0.01490	$0.02937	$0.08089
41	$0.01490	$0.02948	$0.08094
42	$0.01491	$0.02959	$0.08097
43	$0.01492	$0.02969	$0.08101
44	$0.01493	$0.02979	$0.08105
45	$0.01493	$0.02988	$0.08108
46	$0.01494	$0.03008	$0.08230

Table F-8. Emission Damage Costs by HERS Vehicle Class: Rural Minor Arterial[a]

Speed (mph)	Emissions Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
47	$0.01495	$0.03027	$0.08346
48	$0.01496	$0.03045	$0.08458
49	$0.01497	$0.03063	$0.08565
50	$0.01498	$0.03079	$0.08667
51	$0.01500	$0.03109	$0.08855
52	$0.01501	$0.03138	$0.09036
53	$0.01503	$0.03165	$0.09210
54	$0.01504	$0.03192	$0.09377
55	$0.01506	$0.03218	$0.09538
56	$0.01508	$0.03260	$0.09815
57	$0.01510	$0.03301	$0.10083
58	$0.01512	$0.03341	$0.10341
59	$0.01514	$0.03379	$0.10590
60	$0.01516	$0.03416	$0.10831
61	$0.01517	$0.03476	$0.11235
62	$0.01518	$0.03534	$0.11625
63	$0.01519	$0.03590	$0.12003
64	$0.01520	$0.03644	$0.12369
65	$0.01521	$0.03697	$0.12724
66	$0.01521	$0.03750	$0.13090
67	$0.01522	$0.03805	$0.13465
68	$0.01523	$0.03860	$0.13852
69	$0.01524	$0.03916	$0.14249
70	$0.01525	$0.03973	$0.14658
r[b]	6.06%	7.79%	11.25%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-9. Emission Damage Costs by HERS Vehicle Class: Rural Major Collector[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.03599	$0.05627	$0.12618
6	$0.03182	$0.05166	$0.11986
7	$0.02885	$0.04837	$0.11535
8	$0.02662	$0.04590	$0.11197
9	$0.02488	$0.04398	$0.10934
10	$0.02349	$0.04244	$0.10723
11	$0.02239	$0.04077	$0.10379
12	$0.02147	$0.03938	$0.10092
13	$0.02070	$0.03821	$0.09849
14	$0.02003	$0.03720	$0.09640
15	$0.01946	$0.03633	$0.09460
16	$0.01890	$0.03542	$0.09247
17	$0.01841	$0.03462	$0.09059
18	$0.01797	$0.03391	$0.08892
19	$0.01758	$0.03328	$0.08742
20	$0.01723	$0.03271	$0.08608
21	$0.01697	$0.03224	$0.08478
22	$0.01673	$0.03182	$0.08361
23	$0.01651	$0.03144	$0.08253
24	$0.01630	$0.03109	$0.08155
25	$0.01612	$0.03077	$0.08064
26	$0.01596	$0.03053	$0.07995
27	$0.01581	$0.03031	$0.07930
28	$0.01567	$0.03011	$0.07871
29	$0.01554	$0.02992	$0.07815
30	$0.01542	$0.02974	$0.07763
31	$0.01533	$0.02966	$0.07742
32	$0.01524	$0.02958	$0.07722
33	$0.01515	$0.02950	$0.07704
34	$0.01507	$0.02943	$0.07686
35	$0.01500	$0.02937	$0.07670
36	$0.01499	$0.02938	$0.07759
37	$0.01499	$0.02940	$0.07842
38	$0.01499	$0.02942	$0.07922
39	$0.01498	$0.02943	$0.07997
40	$0.01498	$0.02945	$0.08068
41	$0.01499	$0.02956	$0.08073
42	$0.01500	$0.02967	$0.08077
43	$0.01501	$0.02977	$0.08081
44	$0.01501	$0.02987	$0.08085
45	$0.01502	$0.02996	$0.08088
46	$0.01503	$0.03016	$0.08209

Table F-9. Emission Damage Costs by HERS Vehicle Class: Rural Major Collector[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
47	$0.01504	$0.03036	$0.08325
48	$0.01505	$0.03054	$0.08437
49	$0.01506	$0.03072	$0.08543
50	$0.01507	$0.03089	$0.08646
51	$0.01509	$0.03119	$0.08833
52	$0.01510	$0.03148	$0.09013
53	$0.01512	$0.03176	$0.09186
54	$0.01513	$0.03203	$0.09353
55	$0.01515	$0.03229	$0.09514
56	$0.01517	$0.03273	$0.09790
57	$0.01519	$0.03315	$0.10057
58	$0.01521	$0.03355	$0.10315
59	$0.01523	$0.03394	$0.10563
60	$0.01525	$0.03432	$0.10804
61	$0.01526	$0.03492	$0.11206
62	$0.01527	$0.03551	$0.11595
63	$0.01527	$0.03609	$0.11972
64	$0.01528	$0.03664	$0.12338
65	$0.01529	$0.03718	$0.12692
66	$0.01530	$0.03772	$0.13056
67	$0.01530	$0.03827	$0.13430
68	$0.01531	$0.03884	$0.13816
69	$0.01532	$0.03941	$0.14212
70	$0.01533	$0.03999	$0.14620
r[b]	6.05%	7.80%	11.24%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-10. Emission Damage Costs by HERS Vehicle Class: Urban Interstate[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicle	Single-Unit Truck	Combination Truck
5	$0.02562	$0.04511	$0.14771
6	$0.02256	$0.04200	$0.14188
7	$0.02038	$0.03978	$0.13772
8	$0.01875	$0.03811	$0.13460
9	$0.01747	$0.03681	$0.13217
10	$0.01646	$0.03578	$0.13023
11	$0.01566	$0.03454	$0.12709
12	$0.01499	$0.03351	$0.12447
13	$0.01443	$0.03264	$0.12225
14	$0.01395	$0.03189	$0.12035
15	$0.01353	$0.03124	$0.11871
16	$0.01338	$0.03058	$0.11674
17	$0.01324	$0.03000	$0.11500
18	$0.01312	$0.02949	$0.11345
19	$0.01301	$0.02902	$0.11207
20	$0.01291	$0.02861	$0.11083
21	$0.01283	$0.02826	$0.10963
22	$0.01275	$0.02794	$0.10854
23	$0.01268	$0.02765	$0.10754
24	$0.01262	$0.02739	$0.10663
25	$0.01256	$0.02714	$0.10579
26	$0.01250	$0.02697	$0.10515
27	$0.01245	$0.02682	$0.10455
28	$0.01240	$0.02667	$0.10400
29	$0.01235	$0.02654	$0.10349
30	$0.01231	$0.02641	$0.10301
31	$0.01226	$0.02636	$0.10281
32	$0.01221	$0.02632	$0.10263
33	$0.01217	$0.02627	$0.10246
34	$0.01213	$0.02623	$0.10230
35	$0.01209	$0.02619	$0.10215
36	$0.01209	$0.02623	$0.10237
37	$0.01209	$0.02627	$0.10258
38	$0.01209	$0.02630	$0.10277
39	$0.01209	$0.02634	$0.10296
40	$0.01209	$0.02637	$0.10314
41	$0.01211	$0.02648	$0.10378
42	$0.01212	$0.02659	$0.10439
43	$0.01214	$0.02670	$0.10498
44	$0.01215	$0.02680	$0.10553
45	$0.01216	$0.02689	$0.10607
46	$0.01217	$0.02708	$0.10720

Table F-10. Emission Damage Costs by HERS Vehicle Class: Urban Interstate[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicle	Single-Unit Truck	Combination Truck
47	$0.01219	$0.02726	$0.10829
48	$0.01220	$0.02743	$0.10933
49	$0.01221	$0.02759	$0.11032
50	$0.01222	$0.02775	$0.11128
51	$0.01224	$0.02802	$0.11303
52	$0.01225	$0.02828	$0.11471
53	$0.01227	$0.02853	$0.11633
54	$0.01228	$0.02877	$0.11789
55	$0.01229	$0.02901	$0.11940
56	$0.01231	$0.02938	$0.12198
57	$0.01233	$0.02975	$0.12447
58	$0.01235	$0.03010	$0.12687
59	$0.01237	$0.03044	$0.12919
60	$0.01239	$0.03077	$0.13144
61	$0.01241	$0.03129	$0.13520
62	$0.01243	$0.03180	$0.13883
63	$0.01245	$0.03229	$0.14236
64	$0.01247	$0.03276	$0.14577
65	$0.01249	$0.03322	$0.14908
66	$0.01251	$0.03369	$0.15246
67	$0.01253	$0.03416	$0.15592
68	$0.01255	$0.03465	$0.15945
69	$0.01256	$0.03514	$0.16307
70	$0.01258	$0.03563	$0.16677
r[b]	6.77%	8.07%	12.15%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-11. Emission Damage Costs by HERS Vehicle Class: Urban Other Freeway/Expressway[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicle	Single-Unit Truck	Combination Truck
5	$0.02550	$0.04503	$0.14537
6	$0.02246	$0.04192	$0.13959
7	$0.02028	$0.03970	$0.13546
8	$0.01865	$0.03804	$0.13236
9	$0.01739	$0.03674	$0.12995
10	$0.01637	$0.03571	$0.12802
11	$0.01558	$0.03447	$0.12491
12	$0.01492	$0.03344	$0.12231
13	$0.01436	$0.03258	$0.12011
14	$0.01388	$0.03183	$0.11823
15	$0.01346	$0.03118	$0.11660
16	$0.01331	$0.03053	$0.11465
17	$0.01317	$0.02995	$0.11293
18	$0.01305	$0.02943	$0.11140
19	$0.01294	$0.02897	$0.11003
20	$0.01284	$0.02856	$0.10880
21	$0.01276	$0.02821	$0.10762
22	$0.01268	$0.02790	$0.10654
23	$0.01261	$0.02761	$0.10556
24	$0.01255	$0.02734	$0.10465
25	$0.01249	$0.02710	$0.10383
26	$0.01244	$0.02693	$0.10319
27	$0.01238	$0.02678	$0.10260
28	$0.01233	$0.02663	$0.10205
29	$0.01229	$0.02650	$0.10154
30	$0.01224	$0.02637	$0.10107
31	$0.01219	$0.02632	$0.10088
32	$0.01215	$0.02628	$0.10070
33	$0.01210	$0.02624	$0.10053
34	$0.01206	$0.02619	$0.10037
35	$0.01202	$0.02616	$0.10022
36	$0.01202	$0.02620	$0.10044
37	$0.01202	$0.02623	$0.10064
38	$0.01202	$0.02627	$0.10083
39	$0.01202	$0.02630	$0.10102
40	$0.01203	$0.02633	$0.10119
41	$0.01204	$0.02645	$0.10182
42	$0.01205	$0.02655	$0.10242
43	$0.01207	$0.02666	$0.10300
44	$0.01208	$0.02676	$0.10355
45	$0.01209	$0.02685	$0.10407
46	$0.01211	$0.02704	$0.10519

Table F-11. Emission Damage Costs by HERS Vehicle Class: Urban Other Freeway/Expressway[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicle	Single-Unit Truck	Combination Truck
47	$0.01212	$0.02722	$0.10626
48	$0.01213	$0.02739	$0.10728
49	$0.01214	$0.02755	$0.10826
50	$0.01215	$0.02771	$0.10920
51	$0.01217	$0.02798	$0.11093
52	$0.01218	$0.02824	$0.11258
53	$0.01220	$0.02849	$0.11417
54	$0.01221	$0.02873	$0.11571
55	$0.01223	$0.02896	$0.11719
56	$0.01225	$0.02933	$0.11973
57	$0.01227	$0.02969	$0.12218
58	$0.01229	$0.03004	$0.12454
59	$0.01230	$0.03038	$0.12683
60	$0.01232	$0.03071	$0.12904
61	$0.01234	$0.03123	$0.13273
62	$0.01236	$0.03173	$0.13631
63	$0.01238	$0.03222	$0.13978
64	$0.01240	$0.03269	$0.14313
65	$0.01242	$0.03314	$0.14639
66	$0.01244	$0.03361	$0.14972
67	$0.01246	$0.03408	$0.15312
68	$0.01248	$0.03456	$0.15660
69	$0.01250	$0.03504	$0.16016
70	$0.01251	$0.03553	$0.16380
r[b]	6.77%	8.07%	12.15%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-12. Emission Damage Costs by HERS Vehicle Class: Urban Other Principal Arterials[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.02669	$0.04726	$0.12349
6	$0.02369	$0.04387	$0.11733
7	$0.02155	$0.04145	$0.11293
8	$0.01994	$0.03964	$0.10963
9	$0.01869	$0.03823	$0.10706
10	$0.01769	$0.03710	$0.10501
11	$0.01700	$0.03575	$0.10161
12	$0.01643	$0.03462	$0.09877
13	$0.01594	$0.03367	$0.09637
14	$0.01553	$0.03286	$0.09432
15	$0.01517	$0.03215	$0.09254
16	$0.01479	$0.03143	$0.09045
17	$0.01446	$0.03080	$0.08860
18	$0.01416	$0.03024	$0.08697
19	$0.01390	$0.02973	$0.08550
20	$0.01366	$0.02928	$0.08418
21	$0.01345	$0.02890	$0.08291
22	$0.01327	$0.02855	$0.08176
23	$0.01310	$0.02824	$0.08071
24	$0.01294	$0.02795	$0.07974
25	$0.01280	$0.02768	$0.07885
26	$0.01267	$0.02749	$0.07817
27	$0.01256	$0.02732	$0.07754
28	$0.01245	$0.02716	$0.07695
29	$0.01236	$0.02702	$0.07641
30	$0.01226	$0.02688	$0.07590
31	$0.01219	$0.02682	$0.07569
32	$0.01212	$0.02677	$0.07550
33	$0.01206	$0.02673	$0.07532
34	$0.01199	$0.02668	$0.07515
35	$0.01194	$0.02664	$0.07499
36	$0.01194	$0.02668	$0.07522
37	$0.01194	$0.02672	$0.07543
38	$0.01195	$0.02675	$0.07564
39	$0.01195	$0.02678	$0.07583
40	$0.01195	$0.02681	$0.07601
41	$0.01197	$0.02694	$0.07669
42	$0.01198	$0.02706	$0.07733
43	$0.01199	$0.02718	$0.07794
44	$0.01200	$0.02729	$0.07853
45	$0.01201	$0.02740	$0.07908
46	$0.01202	$0.02760	$0.08027

Table F-12. Emission Damage Costs by HERS Vehicle Class: Urban Other Principal Arterials[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
47	$0.01204	$0.02780	$0.08141
48	$0.01205	$0.02799	$0.08249
49	$0.01206	$0.02817	$0.08354
50	$0.01207	$0.02834	$0.08454
51	$0.01209	$0.02864	$0.08637
52	$0.01211	$0.02892	$0.08813
53	$0.01213	$0.02920	$0.08983
54	$0.01214	$0.02946	$0.09146
55	$0.01216	$0.02972	$0.09304
56	$0.01218	$0.03013	$0.09574
57	$0.01220	$0.03053	$0.09835
58	$0.01222	$0.03091	$0.10086
59	$0.01224	$0.03128	$0.10329
60	$0.01226	$0.03164	$0.10565
61	$0.01228	$0.03222	$0.10958
62	$0.01231	$0.03277	$0.11339
63	$0.01233	$0.03331	$0.11707
64	$0.01235	$0.03383	$0.12064
65	$0.01237	$0.03434	$0.12410
66	$0.01239	$0.03485	$0.12766
67	$0.01241	$0.03537	$0.13133
68	$0.01243	$0.03590	$0.13509
69	$0.01246	$0.03644	$0.13897
70	$0.01248	$0.03699	$0.14296
r[b]	6.72%	8.16%	11.19%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-13. Emission Damage Costs by HERS Vehicle Class: Urban Minor Arterial[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.02662	$0.04827	$0.11858
6	$0.02363	$0.04482	$0.11254
7	$0.02150	$0.04236	$0.10823
8	$0.01990	$0.04052	$0.10500
9	$0.01865	$0.03908	$0.10249
10	$0.01765	$0.03793	$0.10047
11	$0.01696	$0.03654	$0.09717
12	$0.01639	$0.03538	$0.09442
13	$0.01590	$0.03440	$0.09210
14	$0.01548	$0.03356	$0.09010
15	$0.01512	$0.03283	$0.08837
16	$0.01475	$0.03209	$0.08635
17	$0.01441	$0.03143	$0.08457
18	$0.01412	$0.03084	$0.08299
19	$0.01386	$0.03032	$0.08157
20	$0.01362	$0.02984	$0.08030
21	$0.01341	$0.02944	$0.07907
22	$0.01323	$0.02908	$0.07796
23	$0.01306	$0.02875	$0.07694
24	$0.01290	$0.02845	$0.07601
25	$0.01276	$0.02817	$0.07516
26	$0.01264	$0.02797	$0.07450
27	$0.01252	$0.02779	$0.07389
28	$0.01242	$0.02762	$0.07333
29	$0.01232	$0.02746	$0.07280
30	$0.01223	$0.02731	$0.07231
31	$0.01215	$0.02725	$0.07211
32	$0.01208	$0.02720	$0.07192
33	$0.01202	$0.02714	$0.07175
34	$0.01196	$0.02710	$0.07158
35	$0.01190	$0.02705	$0.07142
36	$0.01190	$0.02709	$0.07164
37	$0.01191	$0.02712	$0.07184
38	$0.01191	$0.02715	$0.07203
39	$0.01191	$0.02719	$0.07221
40	$0.01192	$0.02722	$0.07239
41	$0.01193	$0.02735	$0.07303
42	$0.01194	$0.02748	$0.07363
43	$0.01195	$0.02760	$0.07421

Table F-13. Emission Damage Costs by HERS Vehicle Class: Urban Minor Arterial[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
44	$0.01196	$0.02772	$0.07477
45	$0.01197	$0.02783	$0.07530
46	$0.01199	$0.02805	$0.07642
47	$0.01200	$0.02826	$0.07750
48	$0.01201	$0.02846	$0.07853
49	$0.01202	$0.02865	$0.07953
50	$0.01204	$0.02883	$0.08048
51	$0.01205	$0.02915	$0.08222
52	$0.01207	$0.02945	$0.08389
53	$0.01209	$0.02975	$0.08550
54	$0.01210	$0.03003	$0.08705
55	$0.01212	$0.03030	$0.08854
56	$0.01214	$0.03075	$0.09110
57	$0.01216	$0.03118	$0.09358
58	$0.01218	$0.03159	$0.09596
59	$0.01220	$0.03199	$0.09827
60	$0.01222	$0.03238	$0.10050
61	$0.01225	$0.03300	$0.10423
62	$0.01227	$0.03360	$0.10784
63	$0.01229	$0.03419	$0.11134
64	$0.01231	$0.03475	$0.11473
65	$0.01233	$0.03530	$0.11801
66	$0.01236	$0.03586	$0.12139
67	$0.01238	$0.03642	$0.12486
68	$0.01240	$0.03700	$0.12844
69	$0.01242	$0.03758	$0.13211
70	$0.01244	$0.03818	$0.13589
r[b]	6.73%	8.17%	11.01%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected annual rate of decline after year 2000.

Table F-14. Emission Damage Costs by HERS Vehicle Class: Urban Collector[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
5	$0.02662	$0.04779	$0.11686
6	$0.02363	$0.04437	$0.11087
7	$0.02150	$0.04193	$0.10659
8	$0.01989	$0.04010	$0.10338
9	$0.01865	$0.03868	$0.10088
10	$0.01765	$0.03754	$0.09889
11	$0.01696	$0.03617	$0.09562
12	$0.01639	$0.03502	$0.09290
13	$0.01590	$0.03406	$0.09060
14	$0.01548	$0.03323	$0.08863
15	$0.01512	$0.03251	$0.08692
16	$0.01475	$0.03178	$0.08492
17	$0.01441	$0.03113	$0.08316
18	$0.01412	$0.03055	$0.08160
19	$0.01385	$0.03004	$0.08020
20	$0.01362	$0.02958	$0.07894
21	$0.01341	$0.02918	$0.07773
22	$0.01323	$0.02883	$0.07663
23	$0.01306	$0.02851	$0.07563
24	$0.01290	$0.02821	$0.07471
25	$0.01276	$0.02793	$0.07386
26	$0.01264	$0.02774	$0.07322
27	$0.01252	$0.02757	$0.07261
28	$0.01242	$0.02740	$0.07206
29	$0.01232	$0.02725	$0.07154
30	$0.01223	$0.02711	$0.07105
31	$0.01215	$0.02705	$0.07086
32	$0.01208	$0.02700	$0.07067
33	$0.01202	$0.02695	$0.07050
34	$0.01196	$0.02690	$0.07033
35	$0.01190	$0.02685	$0.07018
36	$0.01190	$0.02689	$0.07039
37	$0.01191	$0.02693	$0.07058
38	$0.01191	$0.02696	$0.07077
39	$0.01191	$0.02700	$0.07095
40	$0.01192	$0.02703	$0.07112
41	$0.01193	$0.02716	$0.07174
42	$0.01194	$0.02728	$0.07234
43	$0.01195	$0.02740	$0.07291

Table F-14. Emission Damage Costs by HERS Vehicle Class: Urban Collector[a]

Speed (mph)	Emission Damage Cost (2000 $ per vehicle-mile)		
	Four-Tire Vehicles	Single-Unit Trucks	Combination Trucks
44	$0.01196	$0.02752	$0.07345
45	$0.01197	$0.02763	$0.07397
46	$0.01199	$0.02784	$0.07508
47	$0.01200	$0.02804	$0.07614
48	$0.01201	$0.02823	$0.07715
49	$0.01202	$0.02842	$0.07812
50	$0.01204	$0.02860	$0.07905
51	$0.01205	$0.02891	$0.08076
52	$0.01207	$0.02920	$0.08240
53	$0.01209	$0.02949	$0.08398
54	$0.01210	$0.02976	$0.08550
55	$0.01212	$0.03002	$0.08697
56	$0.01214	$0.03045	$0.08948
57	$0.01216	$0.03087	$0.09191
58	$0.01218	$0.03127	$0.09425
59	$0.01220	$0.03166	$0.09651
60	$0.01222	$0.03203	$0.09870
61	$0.01225	$0.03263	$0.10236
62	$0.01227	$0.03321	$0.10591
63	$0.01229	$0.03377	$0.10934
64	$0.01231	$0.03431	$0.11266
65	$0.01233	$0.03484	$0.11588
66	$0.01235	$0.03538	$0.11919
67	$0.01238	$0.03592	$0.12260
68	$0.01240	$0.03648	$0.12610
69	$0.01242	$0.03704	$0.12971
70	$0.01244	$0.03761	$0.13342
r[b]	6.73%	8.17%	10.95%

a. Source: estimated by Volpe Center using procedure described in text.

b. Projected Annual Rate of Decline after year 2000.