PART IV:
OBSERVATIONS AND LESSONS

CONTENTS

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

WesTrack is an accelerated pavement test facility located in the State of Nevada approximately 100 km (60 mi) southeast of Reno. The pavement test facility was designed, constructed, and operated by a team of private companies and universities (the WesTrack team) under contract to the U.S. Department of Transportation's Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP). The project was awarded to the WesTrack team by the FHWA in September 1994. The test track, which includes 26 hot-mix asphalt (HMA) test sections, was designed and constructed between October 1994 and October 1995. Traffic was initiated in March 1996 and was completed in February 1999. Five million 80-kN (18,000-lb) equivalent single-axle loads (ESALs) were placed on the track during the trafficking period.

The initial sponsorship by the FHWA provided for the design of the track, construction of the track, design of the driverless vehicles, trafficking, performance measurements, sampling and testing of materials, preliminary analysis of materials data, and the WesTrack database. The NCHRP provided funding for continued analysis of materials data, development of performance models, development of the performance-related specification (PRS), and reporting.

1.1.1 Objectives

The objectives of the WesTrack research project were as follows:

- Continue the development of PRS for HMA pavements by evaluating the effect of variations in materials and construction quality (asphalt binder content, aggregate gradation, in-place air void content, and so forth) on pavement performance as evaluated by a full-scale accelerated field test track.
- Provide early field verification of the Strategic Highway Research Program's (SHRP) Superpave® volumetric mixture design procedure.

The primary product of this research effort is a PRS for HMA based on performance models derived from the accelerated pavement testing performed at the WesTrack facility. Part 1 of this report defines the PRS developed in this project.

Valuable field verification information for Superpave mixtures has also been obtained and has resulted in changes in some of the original Superpave specification and methods for HMA mixture design. Results of an FHWA-appointed forensic team's analysis (*1*) identifies suggested changes in Superpave resulting from the WesTrack effort.

The scope and objectives of the project concerned two primary types of HMA pavement distress: (1) permanent deformation or rutting and (2) fatigue cracking. Pavements were developed with thicknesses and HMA mixture designs that would rut and fatigue crack during the life of the experiment.

1.2 BACKGROUND

WesTrack involved design, construction, trafficking, sampling, materials characterization testing, performance monitoring, database development, and analysis, among other activities, to produce the primary product of WesTrack, the PRS. During these activities, a significant number of observations were made that are of value to the engineering community in general, but more specifically to those that may be involved in future, full-scale accelerated pavement testing operations, or in the development of models for pavement thickness design or HMA design purposes, or both.

These observations are summarized in this part of the report. The observations are briefly stated with references to WesTrack Technical Reports and graduate student theses that provide the data, their analyses, or both from which the observations were reached. A review of the information presented in this section of the report will provide the reader with insight into the types of additional analysis that can be performed with the WesTrack project data. As with the AASHO Road Test and other large scale research projects, the analysis of the WesTrack data is expected to continue for several decades.

Those researchers interested in using the performance data from WesTrack together with new materials characterization tests and modeling methods may contact the FHWA's Materials Reference Laboratory (MRL) to obtain samples of the binders and aggregates. Large quantities of materials were sampled during construction and stored at the MRL. At the time of preparation of this report, the majority of the aggregate used for original construction had been consumed.

A re-sampling program for the original construction aggregate from Granite Construction's Dayton, Nevada, pit is underway, and this aggregate is expected to be available at the MRL.

1.2.1 Report Organization

This report is organized into four parts:

- Part I: Project Overview.
- Part II: Performance-Related Specification.
- Part III: WesTrack Database.
- Part IV: Observations and Lessons.

Each part of this report has been further divided into chapters and subsections. The overall report format and the individual chapters in this part of the report titled "Observations and Lessons" are shown in Figure 1. Part IV contains the following chapters:

- Chapter 1: Introduction and Background.
- Chapter 2: WesTrack Team.
- Chapter 3: Preconstruction Activities.
- Chapter 4: Construction.
- Chapter 5: Operations.
- Chapter 6: Materials Characterization and Performance Models.
- Chapter 7: Reports and Public Information Activities.

WESTRACK REPORT			
PART I	**PART II**	**PART III**	**PART IV**
Project Overview	Performance-Related Specification	WesTrack Database	Observations and Lessons
1. Introduction and Background 2. WesTrack Team 3. Preconstruction Activities 4. Construction 5. Operations 6. Materials Characterization and Performance Models 7. Reports and Implementation			

Figure 1. Report organization.

CHAPTER 2

WESTRACK TEAM

2.1 ORGANIZATION

The WesTrack team consists of seven organizations, each with specific roles in the project as defined in Table 1 and Figure 2. The Nevada Automotive Test Center (NATC) was the prime contractor and was responsible for managing the project, developing the driverless vehicles, trafficking, and collecting some of the performance information. The test track facility is located on NATC property.

Nichols Consulting Engineers, Chtd. (NCE), was the prime subcontractor and was responsible for project management, construction management of the subgrade and base course placement, sampling, performance monitoring, the WesTrack database, and the PRS.

The University of Nevada, Reno (UNR), University of California at Berkeley (UCB), Oregon State University (OSU), and Harding Lawson and Associates (HLA) were subcontractors to NCE. The UNR was responsible for project management, construction management of the HMA, construction materials sampling, some of the quality assurance testing, and conventional asphalt binder and HMA testing. The UCB was responsible for advanced HMA testing for rutting and fatigue cracking, as well as performance modeling. The OSU was responsible for advanced HMA testing for thermal cracking and water sensitivity, as well as for performance modeling.

HLA assumed responsibility for geometric design of the track, preparation of the plans and specifications, construction inspection, and some of the quality control/quality assurance (QC/QA) testing.

The Granite Construction Company was a subcontractor to NATC and was responsible for construction, rehabilitation, and maintenance of the track. Granite Construction was a member of the research team and was involved in decisionmaking on the project.

The FHWA and NCHRP were considered team members and participated in the decisionmaking. The FHWA was actively involved in the HMA mixture design, as well as QC testing and performance testing. Both FHWA and NCHRP participated in the data analysis, development of the PRS, and reporting.

Personnel involved with the different organizations have been listed in Table 1 and Figure 3 of Part I of this report and will not be repeated here.

Figure 3 of Part IV shows the organizational structure for the project sponsors, research team, and advisory groups. Three advisory groups and an investigative team have been active with the WesTrack project, as shown in this figure. The FHWA was the original and major financial sponsor of the project. An FHWA technical panel was formed to provide input from industry and state highway agencies as well as the federal government. This advisory panel was active primarily during the formation of the experimental plan, construction, and early trafficking. The FHWA also formed a “forensic team” to investigate the premature distress experienced on the replacement sections placed in summer 1997.

The NCHRP provided significant funding to complete the project. An NCHRP panel was formed to guide this portion of the project. As noted in Figure 3 of Part IV, the NCHRP panel and the original FHWA advisory group had several members in common to provide continuity to the project.

The WesTrack team used a small group of consultants to provide an external review and consulting function for the project. This group consisted of individuals who were part of the AASHO Road Test research team (1959–62), researchers on earlier PRS projects, and state highway department personnel familiar with statistical specifications.

2.2 OBSERVATIONS

A technically diverse research team was needed for this project. Each member of the research team and his/her respective organization provided unique skill sets to the project. General civil engineers, pavement design engineers, materials engineers, mechanical engineers, electrical engineers, computer scientists, and statisticians were used on the project. The diversity of the skill sets was sufficient to accomplish the project, although the study could have benefited from additional statistical input.

To provide the necessary level of expertise and testing equipment capability, a research team was assembled. Five of the seven primary organizational members of the research team were located within 100 km (60 mi) of Reno, Nevada. The UCB is 350 km (220 mi) and OSU is 650 km (400 mi) from Reno. This dispersion of team members presented few problems. Travel for project staff meetings was not a serious problem. The shipping of materials could have been reduced and more convenient interaction of the research team would have been possible if the individuals had been in one location.

With several key members of the team located in Reno, the remoteness of the track was inconvenient at times. On the other hand, the ability of the team to design, receive approval from regulatory authorities, and construct the track within a 1-year period was largely due to the track's location and due to the existing vehicle testing programs at the site.

While the AASHO Road Test model of using a full-time staff living near and working at the test track would have been the best possible way for staffing this project, the budget and project concept did not allow for this type of staffing plan.

The NATC was the prime contractor and was responsible for overall project management. Technical management was performed by co-principal investigators at NCE and the UNR. This division of fiscal management responsibility and technical management responsibility presented few problems during the conduct of the project. A more efficient project management would have been obtained with full-time co-principal investigators, but the budget was insufficient to provide for full-time staff at this level.

With several organizations involved, one persistent problem during the project was tracking expenditures versus budgets. The division of budgets among the research agencies at the start of the project with adjustments during the project was effective. The billing for expenditures from two of the universities was largely not timely and not supported with information required by the project sponsors. One of the universities would not bill for services for several months at a time and the "float" (time between actual expenditures and expenditures appearing on central billing systems) was excessive.

The FHWA and NCHRP, as well as the internal WesTrack team advisory committees (Figure 3), were effective in providing guidance for the project. Additional meetings and more time for review of project reports would have been beneficial to the project research team.

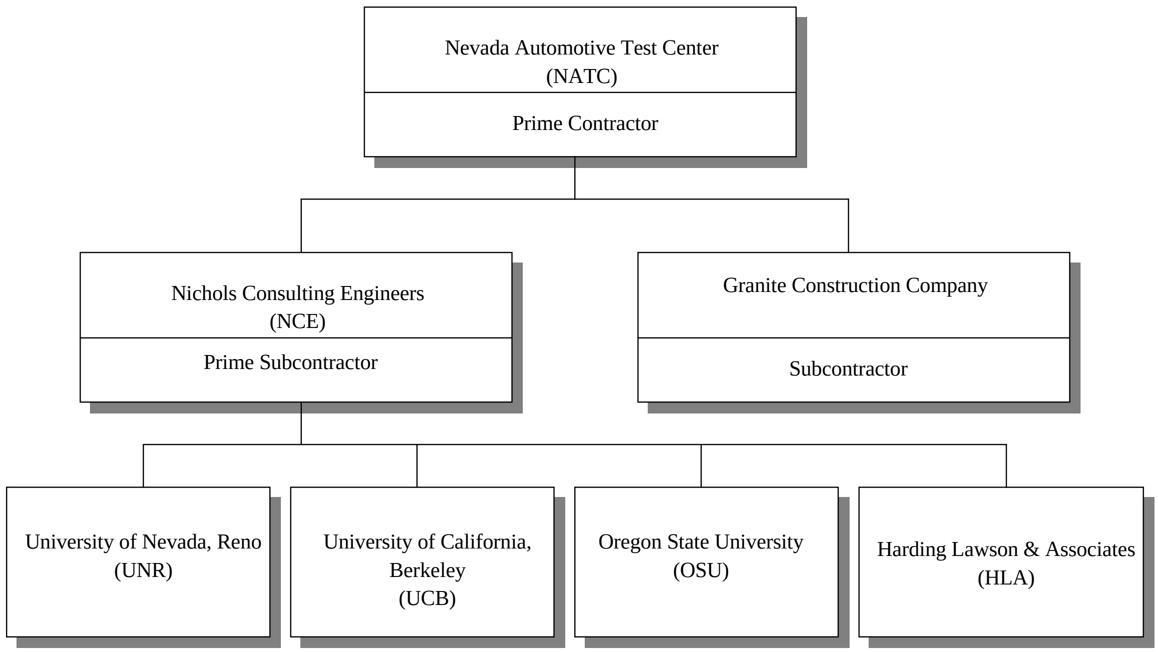


Figure 2. WesTrack team organizational structure.

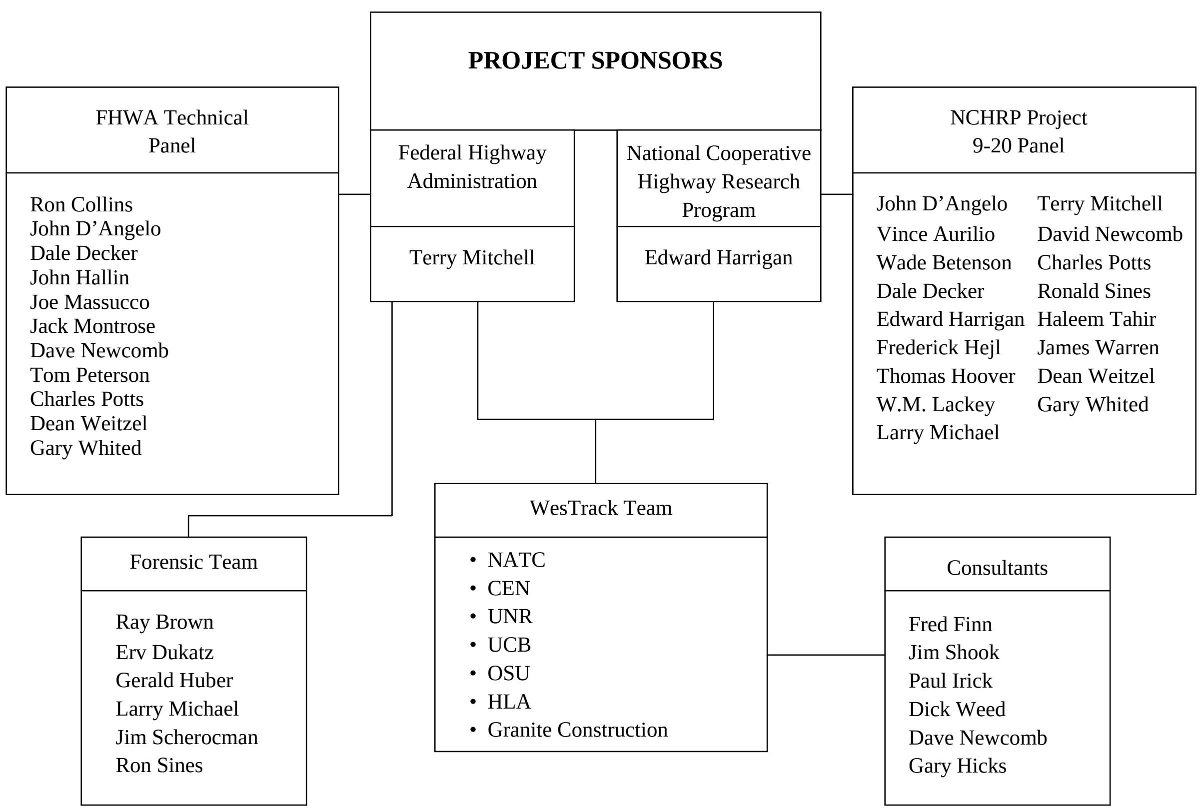


Figure 3. Advisory groups.

TABLE 1 WesTrack team

Organization/Location	Primary Role(s)	Principal Personnel
Nevada Automatic Test Center (Silver Springs, Nevada)	• Prime contractor • Project management • Driverless vehicle development • Trafficking • Performance monitoring	• Henry Hodges, Jr. • Colin Ashmore • Paul Pugsley • Dave Heinz • John Knowles • Randy Carlson
Nichols Consulting Engineers, Chtd. (Reno, Nevada)	• Prime subcontractor • Project management • Construction management • Sampling • Performance monitoring • Relational database • Performance-related specification	• Sirous Alavi • Weston Ott • Joseph Mactutis • Larry Musa • Steve Seeds • Todd Scholz
University of Nevada, Reno (Reno, Nevada)	• Project management • Construction management • QA testing • Conventional testing	• Jon Epps • Adam Hand • Peter Sebaaly
University of California at Berkeley (Berkeley, California)	• Permanent deformation testing • Fatigue testing • Performance prediction models	• Carl Monismith
Oregon State University (Corvallis, Oregon)	• Thermal cracking testing • Water sensitivity testing • Performance prediction models	• Rita Leahy
Harding Lawson and Associates (Reno, Nevada)	• Geometric design • Plans and specifications • Construction inspection • QC/QA testing	• Stuart Dykins • John Welsh
Granite Construction Company (Reno, Nevada)	• Construction • Rehabilitation • Maintenance	• Mike Robinson • Kevin Robertson
Federal Highway Administration (Washington, D.C.)	• Project oversight • Mix design • QC testing • Performance testing of hot-mix asphalt	• Terry Mitchell • Chris Williams • John D'Angelo • Ray Bonaquist
National Cooperative Highway Research Program (Washington, D.C.)	• Project oversight • PRS and report review	• Edward Harrigan

CHAPTER 3

PRECONSTRUCTION ACTIVITIES

3.1 INTRODUCTION

A number of activities were performed by the WesTrack team prior to the construction of the test track. For convenience of reporting these activities have been grouped together and titled “Preconstruction Activities.” These preconstruction activities included the following:

- Experiment design.
- Site evaluation.
- Geometric design.
- Driverless vehicle development.
- Pavement instrumentation.
- Geotechnical investigation.
- Pavement thickness design.
- QC/QA plan development.
- Plans and specifications.
- HMA mixture design.

Observations relative to each of these activities are described in the following sections.

3.2 EXPERIMENT DESIGN

Seven experimental factors related to the HMA surface layer were initially considered in the development of the experimental design:

- Asphalt binder type.
- Aggregate type, shape, and surface texture.
- Aggregate gradation.
- Asphalt binder content.
- In-place air voids.
- HMA thickness.

Observations relative to these items are presented in the following subsections.

3.2.1 Asphalt Binder Type

The asphalt binder type or grade was selected based on the Superpave PG binder selection procedure for the test track environment (*2*). The asphalt binder high temperature grade was not increased due to the rate that traffic was applied to the track because, at the time the binder grade was selected, it was not clear that the Superpave design guidelines were based on the application of projected ESALs over a 20-year period. In addition, an increase in grade of the binder was not well supported by technical information. The low temperature grade was considered adequate for the relatively short life of the track and lowering of the low temperature grade would require the use of a polymer-modified asphalt binder. The use of polymer-modified binders at the test track was not desired because the Superpave binder grading system was largely based on research performed on “neat” binders.

While arguments can be presented for selection of a higher high-temperature grade at WesTrack, the selection did follow the technically supported Superpave guidelines. If additional WesTrack-type experiments are performed in the future, polymer-modified asphalt binders should be considered as one of the variables. Comparative pavement performance information to support the expanding use of polymer-modified asphalt binders is minimal.

Additional information on the asphalt binder selection process used for WesTrack and on the binder properties can be found in WesTrack Technical Reports UNR-1 (*3*) and UNR-2 (*4*), respectively.

3.2.2 Aggregate Type, Shape, and Surface Texture

Selection of the aggregate source largely determines the mineralogy, shape, and surface texture of the aggregate (unless different types of crushing and sizing equipment can be used). The planned use of a partially crushed gravel and a quarried rock was consistent with the project objective. Numerous mixture designs were performed with the quarried rock in an attempt to formulate an acceptable Superpave mixture. These efforts failed and the partially crushed gravel was used for all three mixture gradations placed at WesTrack. The use of additional baghouse fines to produce one of the three mixtures placed at WesTrack allowed for the development of pavement performance relationships with 0.075-mm (No. 200) sieve material as a performance predictor.

The replacement sections at WesTrack used a quarried rock that was 100 percent crushed. Thus, evaluations have been performed on both partially and highly crushed aggregates.

If additional WesTrack-type experiments are performed in the future, various types of aggregates should be investigated. Since neither of the aggregates used on the track has an extremely rough surface texture, consideration should be given to use of an aggregate with a very rough surface texture in future experiments.

Additional information that defines the properties of the aggregates used at WesTrack can be found in WesTrack Technical Reports UNR-4 (*5*), UNR-5 (*6*), and UNR-20 (*7*).

3.2.3 Aggregate Gradation

The fine- and coarse-graded Superpave gradations in the original sections were selected to provide a comparison between the extremes of the gradations defined by the Superpave system. A fine-plus gradation was used to replace a coarse-graded, 100 percent crushed aggregate. The fine-plus gradation was obtained by adding additional baghouse fines to the fine-graded mixture. The replacement sections were placed with a coarse gradation.

The differences in performance of the fine- and coarse-graded Superpave mixtures were significant at WesTrack. Differences in performance from both permanent deformation and fatigue cracking were evident. The coarse-graded mixtures appeared to be more sensitive to asphalt binder content, percent passing the No. 200 sieve, and in-place air voids than the fine-graded mixtures. The coarse-graded mixtures placed at WesTrack must have low in-place air voids and lower than Superpave design asphalt binder contents to perform at an acceptable level.

Because the performance of the mixtures at WesTrack were very dependent on gradation, it is recommended that future experiments on test tracks consider aggregate gradation as an important variable.

Additional information defining the gradation of the aggregates used during mixture design and the gradations actually placed is available in WesTrack Technical Reports UNR-6 (*8*), UNR-7 (*9*), UNR-22 (*10*), and UNR-24 (*11*).

3.2.4 Asphalt Binder Content

The optimum asphalt binder content was selected as part of the Superpave mix design process. The range in asphalt binder contents was set at ±0.7 percentage points from the optimum or target value established during mix design. This range of asphalt binder content was selected to provide for a practical and a statistically significant separation of binder contents among the low, optimum, and high binder content mixtures. In addition, this range of asphalt contents was considered adequate to provide for both good- and poor-performing pavements from both permanent deformation and fatigue cracking standpoints.

A separation of asphalt binder contents was obtained on mixtures placed during original construction. Less of a separation in asphalt binder contents was obtained on the replacement sections. Based on the performance differences and the practical degree of asphalt binder content control that is possible during the construction of a test track of this type, it is believed that the selection of a separation of ±0.7 percentage points from the design value is appropriate.

The magnitude of the asphalt binder content influences the permanent deformation and fatigue cracking performance of pavements as defined by the WesTrack experiment. The coarse-graded Superpave mixtures appear to be more sensitive to asphalt binder content than the fine-graded mixtures. Thus, aggregate gradation influences the sensitivity of HMA to asphalt binder content. Although this appears to be contrary to highway agency experience with these two types of mixtures (at least in the pre-Superpave era), long-term observations of field performance are desirable. In future test track experiments, the interaction of aggregate gradation and asphalt binder content should be studied to define what types of mixtures are relatively insensitive to changes in asphalt binder content.

Additional information that defines the asphalt binder content of the HMA mixtures placed at WesTrack can be found in WesTrack Technical Reports UNR-15 (*12*) and UNR-17 (*13*).

3.2.5 In-Place Air Voids

The target in-place air void content selected for WesTrack mixtures was 8 percent, based on calculations dependent on the bulk specific gravity of core samples and the theoretical maximum specific gravity of the HMA. The range of in-place air voids from this target value was ±4 percentage points (4, 8, and 12 percent air voids). This range was selected to provide for both a practical separation and a statistically significant separation of the low, medium, and high in-place air voids in the pavement. In addition, this range of in-place air voids was considered adequate to provide for both good- and poor-performing pavements from permanent deformation and fatigue cracking standpoints.

A statistically significant separation of in-place air voids was obtained during placement of the HMA mixtures at WesTrack. In general, the control of in-place air void content achieved by controlling the temperature of the mixture and the rolling patterns was good.

The magnitude of the in-place air voids influences the permanent deformation and fatigue cracking performance of the pavements placed at WesTrack. The coarse-graded Superpave mixtures appear to be more sensitive to in-place air void content than the fine-graded Superpave mixtures. Thus, aggregate gradation influences the sensitivity of an HMA to in-place air void content. In future test track experiments, the interaction of aggregate gradation and in-place air void content should be studied to define what types of mixtures are relatively insensitive to changes in in-place air void contents.

Additional information that defines the in-place air void content of the HMA mixtures placed at the track can be found in WesTrack Technical Reports UNR-12 (*14*) and UNR-13 (*15*).

3.2.6 Hot-Mix Asphalt Thickness

The experiment design at WesTrack used a single thickness of the HMA, base course, engineered fill, and compacted subgrade. Because the experiment was established to study the relative performance of HMA placed at different asphalt binder contents, different in-place air voids, and different gradations, the pavement structural section was fixed. Both construction costs and vehicle operating costs limited the experiment to a single thickness. WesTrack was not an experiment directed toward providing an extensive amount of information for thickness design model development.

The thickness selected for WesTrack provided fatigue failures in a significant number of the sections placed. Some members of the FHWA forensic team believe that relative performance of the mixtures placed at WesTrack would have been significantly different if a stiffer pavement section had been used. The thickness design methodology was discussed in Part I of this report; additional details can be found in reference 2.

3.3 SITE EVALUATION

Three issues were addressed during the site evaluation portion of this study:

- Effects of prevailing climate on the pavement performance.
- Impact of the test track on the environment.
- Potential for flooding.

Specific information on the evaluation of the soil support at the site was described in Part I of this report.

The high desert climate of northern Nevada is an ideal climate for test tracks evaluating the relative permanent deformation (rutting) and fatigue cracking performance of HMAs placed with different mixture variables. The hot summer months allow for rutting to occur in those mixtures prone to permanent deformation. The colder winter months allow for the relatively rapid propagation of fatigue cracks.

The seasonal variability of the subgrade materials is always a problem with accelerated testing on test tracks and other facilities open to the elements. Seasonal variability as a result of moisture, freezing, and the spring thaw can be a problem in more northern climates. Freezing of the unstabilized materials (subgrade, engineered fill, and base course) was not a problem at WesTrack, neither was the spring thaw. Seasonal variability in stiffness of the unstabilized pavement layers did exist at WesTrack, but this cannot be avoided on test track facilities of this type. Change in elevation and depth of the ground water table at the site were partially responsible for this seasonal variability. Perhaps a track site with a more stable water table or a water table at greater depths would reduce the seasonal variability of the unstabilized materials. Water-deposited materials in larger river systems probably provide more uniform materials than other locations. However, the ground water table can be an issue at this type of site. Placing an impermeable membrane on the surface of the unstabilized portion of the pavement cross section (gravel shoulders, engineered fill, and so forth) may help limit the seasonal variability.

Securing an environmental impact clearance was not an issue at WesTrack. The remoteness of the site and the use of the site for vehicle testing allowed for rapid approval by governmental agencies. This was a significant advantage that this site offered because the design, environmental approvals, and construction could be completed in a 1-year period.

A greater than 100-year flood occurred during the trafficking at WesTrack. This flood, while unexpected, was typical (climatically) of major floods recorded along the Carson River. Only minor damage—erosion in the shoulder areas of a few sections—resulted at the track. Traffic was removed from the facility until the deflections of the pavement reached the same levels as were present at the track prior to flooding.

All factors considered, the site is excellent for conducting accelerated pavement testing. Frequent nondestructive testing with a falling weight deflectometer (FWD) allowed for seasonal variability to be considered, as well as the stiffness of the various layers in the model development effort. Additional information relative to site selection can be found in reference 2.

3.4 GEOMETRIC DESIGN

The geometric design used at WesTrack provided an excellent balance among economics, safety, and constructability. The length of the test sections, the number of test sections, the maximum allowable superelevation, and the truck speeds largely determined the length of the track. Section lengths were established based on vehicle dynamics, construction uniformity, performance monitoring, destructive sampling, and cost considerations. The number of sections was dictated based on the experimental design needs and costs of construction and operation. Superelevation in excess of about 18 percent is difficult to construct and can cause driverless vehicle control problems. Truck speeds were established as close to highway operational speeds as practical with consideration given to vehicle operating costs and construction costs.

Safety considerations suggested the use of spiral curves and of shoulders and vehicle recovery features including roadside safety slopes. The inside shoulder was 3.7 m (12 ft) wide and was used as a trial lane to refine the construction operation for the placement of uniform HMA. Section lengths were in part established by constructability considerations.

The geometric design used at WesTrack served the project very well. Many of the design features at WesTrack were incorporated in the accelerated pavement test track constructed subsequently at Auburn University.

Additional details on geometric design considerations can be found in WesTrack Technical Report NCE-2 (*16*) and reference 2.

3.5 DRIVERLESS VEHICLE DEVELOPMENT

The driverless vehicles were developed by the NATC. The driverless vehicles were controlled by a "guide-by-wire-system." Key features of the system included traffic control, onboard vehicle control computers, speed control systems, brake control systems, lateral and longitudinal control systems, vehicle instrumentation, and truck health systems. The guide-by-wire systems proved to be effective. The placement of the wire in the pavement was not automated for this relatively small test track. The wire was initially placed in 19-mm (3/4-in.) conduit at the top of the base course layer. Replacement of the wire was later necessary due to thermal expansion problems in the conduit and to wire movement and "pinching" of the conduit during construction. The replacement wire was placed near the surface in a sawcut. This location for the wire becomes a problem during pavement rehabilitation and maintenance operations.

The only serious mishap at the track was caused by a failure in the traffic control systems from an information overload of the computers coupled with a brake system failure. One of the four trucks was lost in a two truck accident.

A failure of the brake system was also responsible for a minor incident in which a truck ran off the track at a slow speed. The vehicle control system was responsible for this incident, which occurred as the truck exited a curve where the guide wire was offset from a true line and some roughness was present in the pavement surface.

The truck health system was responsible for delays in final development of the system. More than 100 vehicle health signals were monitored. If these vehicle health signals were outside of certain limits, the trucks were instructed to "shut down." The sorting out of the limits for shut down was very time-consuming during the developmental stages of the driverless vehicle research effort.

An extremely large amount of track instrumentation data is available and can be used to define truck dynamics and tire/pavement interaction effects. These data have not been analyzed in the current study.

The systems used at WesTrack afforded the opportunity to place 5 million ESALs on the pavement with trucks traveling more than 1.3 million km (820,000 mi) without loss of life or injury. The per km costs of this driverless system were below the inflation-adjusted traffic costs on the AASHO Road Test.

Additional information on the development of the driverless vehicle technology can be found in reference 2.

3.6 PAVEMENT INSTRUMENTATION

A limited amount of pavement instrumentation was installed at WesTrack to monitor climate conditions, pavement temperatures and moisture conditions, strains on the underside of the HMA, and subsurface permanent deformation. The climate collection instrumentation performed at a high level. The strain gages placed on the underside of the HMA had a performance life of approximately 1 million ESALs. The subsurface permanent deformation measurement devices were only partially successful in supplying data.

The low level of pavement instrumentation installed at WesTrack resulted from the nature of the experiment and budget considerations. Most of the data collected with this instrumentation have not been carefully analyzed. The pavement instrumentation data are contained in the WesTrack database presented in Part III of this report.

3.7 GEOTECHNICAL INVESTIGATION

A geotechnical investigation and nondestructive test program was performed at WesTrack to characterize the soil conditions at the site, locate the track within the available area of the most uniform subgrade conditions, and provide some basis for the structural design of the pavement section. Test pits, borings, and FWD testing were performed at the site. The natural soil at the site consisted of varying proportions and blends of fine-grained clays, sands, and silts. The soils were deposited by the Carson River and were reasonably uniform.

The test pits and borings were used to obtain soil samples and define uniformity on a relatively large scale. The FWD testing was used to backcalculate modulus values and to establish uniformity of the subgrade on a smaller scale.

Ideally, more than one potential location for the track site should have been investigated and the most uniform of the sites selected for the track location. Uniformity should be measured by subgrade resilient modulus or stiffness and low variability of the stiffness with seasons. The lead time for construction and budget considerations prevented the evaluation of more than one site. Additional sites above the Carson River flood plain were available at the NATC facility.

Considerable difficulty was experienced in using backcalculation procedures for determining subgrade modulus values. The use of FWD on soft soils and with water tables relatively near the surface creates problems with backcalculation procedures. A considerable amount of additional analysis can be performed on the FWD data collected at WesTrack.

3.8 PAVEMENT THICKNESS DESIGN

Pavement thickness designs were developed for three areas at WesTrack: tangent sections, turnarounds, and ramps. The thickness designs on the tangent sections were based on the use of layered elastic computer programs to produce stresses, strains, and deflections in the pavements for simulated conditions of material properties and wheel loads. The pavement sections were designed such that the permanent deformation (rutting) of the pavement would largely not result from permanent deformation in the subgrade, engineered fill, and base course layers because the objective of WesTrack was to determine the rutting in the pavement as a result of the permanent deformation in the HMA layer.

The pavements were also designed to produce fatigue failures. The tangent sections were designed for failure within 10 million 80-kN (18,000-lb) ESALs with a 90 percent reliability. The 90 percent reliability was used to provide a high potential for distress to occur on the track. The anticipated fatigue life of the pavement at the 50 percent reliability was 3.3 million ESALs for a typical HMA.

The thickness designs used on the tangent sections produced pavement sections that had little permanent deformation due to the subgrade, subbase, and base course layers. Almost all of the rutting in the pavement surface was due to the permanent deformation in the HMA.

Fatigue occurred in more than one-half of the sections placed at WesTrack at traffic levels of 5 million ESALs. If 10 million ESALs were placed on the track, it is likely that the remaining sections would have experienced fatigue failures.

The data available from WesTrack can be used to calibrate pavement thickness design models. Although all test sections on the tangents were of equal thickness, some variation existed in the subgrade, engineered fill, and base course modulus values as measured by the FWD. In addition, the modulus values of the HMA varied. Because the stiffnesses of the various materials that made up the structural layers were measured as a function of time, WesTrack offers a unique opportunity to evaluate the influence of changes in pavement structural properties with time on pavement performance and hence thickness design models.

3.9 QUALITY CONTROL/QUALITY ASSURANCE PLANS

A significant effort was expended to establish QC/QA sampling and testing plans. Chapter 12 of reference 2 and WesTrack Technical Reports UNR-18 (*17*) and UNR-19 (*18*) contain the background information used to develop the plans. The purpose for developing these plans was to describe the types and frequency of tests that were to be used for QC/QA purposes and that were to control the uniformity of the materials placed at WesTrack.

The QC/QA plan developed was somewhat ambitious relative to the time available for placement of the HMA sections. Because eight or nine sections of HMA (of different properties) were placed daily, the amount of testing required to maintain control of the process was very large. Although the QA crew size and facility size were large (four trailers and more than 20 technicians), additional testing capability would have been beneficial.

Test tracks with characteristics similar to WesTrack should consider increasing the size of the QC crews and facilities, reducing the number of sections placed per day, or increasing the number of days between placing sections. Longer lead times for calibration of equipment and mixture design are also desirable.

3.10 PLANS AND SPECIFICATIONS

WesTrack Technical Report NCE-2 (*16*) contains plan sheets describing the track geometrics and pavement cross sections. Specifications for the project are contained in WesTrack Technical Report UNR-31 (*19*). These plans and specifications served their intended purpose during the construction of WesTrack.

Additional efforts should have been expended to compare the “desired targets and variabilities” as established by the specification with the “as-constructed” properties for the subgrade, engineered fill, and base course materials. Some additional comparisons between specification limits and as-constructed properties would have been beneficial for the HMA materials as well.

3.11 HOT-MIX ASPHALT MIXTURE DESIGN

3.11.1 Asphalt Binder Selection

The asphalt binder selection was based on the use of the Superpave performance-graded (PG) binder system. Although concern has been expressed with the asphalt binder grade selection, the WesTrack team considered it proper for the test site and traffic. Because the type of binder was not considered to be as critical a variable as other factors on the WesTrack project, only one binder grade was selected. Future accelerated test track research studies should consider including several binder types and grades in their experimental plans.

3.11.2 Aggregate Selection

Selection of the aggregates for the coarse-graded mixtures in the WesTrack project included partially crushed gravels and a quarried andesite aggregate. Fine-graded mixtures prepared from a partially crushed river gravel were also included in the experimental sections. Additional aggregates and gradations need to be considered in future accelerated test track research efforts. The influences aggregate properties and gradation have are much more important than originally estimated based on the results from WesTrack.

3.11.3 Hot-Mix Asphalt

HMA mixture design information for both the original construction and the replacement sections is contained in

WesTrack Technical Reports UNR-6 (*8*) and UNR-7 (*9*). A significant number of mixture designs were performed to obtain the mixtures. Difficulties obtaining the desired aggregates, aggregate gradations, and volumetrics created the majority of the problems for the mixture designs for the original construction sections. Variabilities in aggregate properties and in stockpile gradations were problems experienced during the design of the replacement sections.

Although several months were available to design the HMA mixtures for WesTrack, this proved to be insufficient time to develop all of the desired Superpave volumetric mixture design information and supporting Marshall and Hveem data. In addition, the original plans for WesTrack contained time for performing the Superpave performance tests. Unfortunately, many of the Superpave performance tests had not been formalized or the time required to perform these tests was excessive considering the difficulties experienced with obtained Superpave volumetric design.

On future projects of the WesTrack type, 6 to 8 months of lead time should be allocated to the mixture design effort after the aggregates have been selected. As a minimum, laboratory performance tests and volumetric mixture designs should be completed prior to construction. In addition, the sensitivity of the mixtures to the main variables in the experimental plan (asphalt binder content, percent passing the No. 200 sieve, and in-place air voids) should be investigated by using performance tests prior to placing the test sections.

CHAPTER 4

CONSTRUCTION

This chapter briefly defines the observations and lessons learned during the construction of WesTrack. For convenience, the construction operations have been grouped together under the headings of subgrade and engineered fill, base course, and HMA.

4.1 SUBGRADE AND ENGINEERED FILL

To produce as uniform as possible subgrade and engineered fill material, the natural soil was excavated and distributed around the track with self-elevating, self-propelled earth movers. The material was further blended with an agricultural disc which aided in breaking up soil agglomerations and allowed for more uniform moisture content. The material was placed in approximately 75-mm (3-in.) lifts and was further blended and shaped with a motor grader.

The in-place density and moisture contents were controlled within the desirable limits for the majority of the sections. To obtain the final grade on the engineered fill, fine grading was performed while the engineered fill material was moist. A pulverizing mixer was used to mix the top 150 mm (6 in.) of the engineering fill prior to final compaction. A laser system was not effective in controlling the final grade elevations of the engineered fill. A wire line set on each side of the tangents and automatic cross-slope control (verified with control hubs) were used to produce the final grade on the engineered fill and the base course.

Once the final density of the subgrade and engineered fill was obtained, construction traffic was not allowed on the track. The engineered fill was kept moist after its construction and prior to the placement of the base course to maintain a uniform moisture content.

Statistical summaries should be prepared and compared to the specifications to better understand the quality of the engineered fill. In addition, the FWD data obtained on the subgrade and engineered fill layers could be more thoroughly analyzed. The concept of determining layer modulus values for the different material layers as a pavement is constructed by use of FWD data needs to be more thoroughly analyzed. Theoretically, FWD data could be obtained after completion of the different layers in a pavement and, depending on the stiffness of these layers (as-constructed), the final thickness of the HMA layers could be established. The HMA layer thickness would, therefore, be based on as-constructed properties rather than laboratory-determined properties. Improved life-cycle costs of pavements would result from this approach to pavement thickness design.

A limited number of strength characterization tests (CBR, R-value, and resilient modulus) were performed on the subgrade and engineered fill material. Additional testing would have been valuable to determine the section-to-section variability of the load-carrying ability of the subgrade and engineered fill.

4.2 BASE COURSE

The base course material was obtained from a pit near the WesTrack site. Initially, a single stockpile was produced but the variability within this stockpile was excessive; the aggregate produced for the base course was then separated into four stockpiles that were subsequently recombined with a four-bin feeder system and mixed with a pugmill. The objective of this added effort was to produce a uniform base course material.

For pavement test tracks, the separation and recombinations of aggregate to achieve a more uniform product is desirable. The data upon which these decisions were made have not been placed into a WesTrack technical report. The benefits derived from a one- versus a four-stockpile system to produce a uniform base course have not been quantified.

The base course was hauled in 10-wheel dump trucks from the base course blending area to the track and back-dumped onto the finished subgrade. This hauling and initial placing operation was designed to keep base course haul traffic off the finished subgrade and engineered fill. The use of this hauling and placing approach placed the trucks on the base course layer prior to final compaction and not on the finished subgrade and engineered fill. This approach should be considered for future test track construction.

The QC/QA information obtained on the base course has not been thoroughly analyzed and placed in a WesTrack technical report. This effort should be undertaken.

During the placement of the replacement sections at WesTrack, some of the original construction HMA sections were removed and replaced. During this operation, the base course was disturbed and some base course material was removed. Additional base course material was placed and the grade reestablished. Working in a confined area (the hole created by removal of only the test lane) caused some variability problems that were not quantified except with limited moisture/density tests and with FWD tests performed on the surface of the HMA. These data need to be summarized and placed in a WesTrack technical report.

Future replacement or reconstruction operations at WesTrack or similar APT sites should allow for re-mixing of the existing base course and the addition of new base course material prior to compacting and reestablishing the grade. Improved methods of obtaining the desired grade control in limited work areas are also needed.

A limited number of strength characterization tests (CBR, R-value, and resilient modulus) were performed on the base course material. Additional testing would have been valuable to determine the section-to-section variability of the load-carrying ability of the base course.

4.3 HOT-MIX ASPHALT

4.3.1 Construction

The placement of relatively short sections of the HMA presented special problems, one of which was smoothness control. When paving machines start, the screeds which control thickness usually rise and then fall. This creates thickness control and smoothness problems. Because the initial portion of each section was a transition section, the nonuniformity in terms of thickness did not affect the results of the experiment. However, the roughness at the start of each section was a problem and almost without exception, the start of each section and the end of the previous section were subjected to diamond grinding to provide the desired smoothness. The cost of diamond grinding should be included in the cost of construction or improved methods should be developed for starting paving operations.

The first 15 to 20 m (50 to 65 ft) of each section were used to allow for the laydown machine start-up roughness to dissipate and to allow the rollers to enter the test section without traveling on the end of the previously placed section. Often, this initial part of the section did not receive adequate compaction and premature distress resulted. Future projects should ensure that satisfactory compaction be provided at the start of the sections to provide for longer performance.

The end of each section was paved approximately 10-m (30-ft) beyond the designed end of the section to allow the rollers to remain at their usual compaction speed until they moved beyond the designed end of the section and reversed direction. The length of this extension on the section also allowed for any end-of-the-section segregation to be localized on a portion of the pavement section that would be removed. The 10-m (30-ft) extension was removed prior to placement of the next section. The length of this extension at the end of each section was not adequate in some cases. Longer extension lengths should be considered for future test track construction operations.

A material transfer device was used for placement of the HMA sections. Initial trial pavement sections placed on the "on" and "off" ramps indicated that a material transfer device would be needed to avoid segregation and to provide additional hot-mix storage close to the paver. With a material transfer device, the paving of a test section was continuous. The paving machine would start and not stop until the entire test section was paved. The increased storage capacity provided by the expanded hopper on the laydown machine and the storage in the material transfer device, plus an additional transfer of material, provided sufficient material to pave the entire section without stopping. Very few sections were placed where the paving machine was stopped within a test section. Good coordination among the trucks, material transfer device, and paving operation was necessary to provide continuous paving.

4.3.2 Quality Control/Quality Assurance—Original Construction

The QA sampling and test plan for original construction is detailed in WesTrack Technical Report UNR-18 (*17*). QA test results can be found in the following reports:

- Asphalt Binder Content — WesTrack Technical Report UNR-15 (*12*)
- Hydrated Lime — WesTrack Technical Report UNR-3 (*20*)
- Aggregate Gradation — WesTrack Technical Report UNR-22 (*10*)
- Volumetrics — WesTrack Technical Report UNR-9 (*21*)

A considerable amount of additional analysis can be performed on these data sets and the QC data sets from the original construction sections. References 22 through 26 provide an indication of the types of analyses that can be performed.

4.3.2.1 Asphalt Binder Content

Calibration of ignition ovens that were used for determining the asphalt binder content was a major problem experienced at WesTrack. In the end, solvent extractions (reflux) were used to calibrate the QA asphalt binder contents results used for preparing the performance models at WesTrack.

A relatively large experimental program should be undertaken to calibrate the equipment used to determine asphalt binder content prior to the placement of test sections on test tracks.

4.3.2.2 Aggregate Gradation

Aggregate gradations were determined after ignition testing and after reflux extraction testing. An adequate correction factor between ignition oven gradations and known gradations used in calibration studies could not be developed.

4.3.2.3 Hydrated Lime

Hydrated lime was used at WesTrack. Its properties were certified by the lime supplier. Postconstruction QC testing was performed on samples of lime obtained during production. These samples were also tested by the lime supplier. WesTrack Technical Report UNR-3 (*20*) contains the lime property data.

No known problems were experienced with the use of this QC/QA program for the hydrated lime.

4.3.2.4 Volumetric Data

Superpave volumetric data were obtained with two different compactors during the placement of the original sections. Because of the number of sections placed during a given day, the amount of volumetric data on any one day was limited and the variability of the volumetric parameters created difficulties in interpreting these data sets. However, the general trends in the volumetric data indicated that the desired properties were being obtained.

The QA data collected after the construction was completed largely confirmed the QC data obtained during construction. The numbers of compactors and personnel needed to obtain volumetric data on four to five samples per section during construction would have exceeded the budget and time constraints.

Each day during construction, meetings were held with plant personnel and inspectors to review the previous day's QC data and to discuss the construction schedule. These meetings were a valuable communication tool and generated the teamwork necessary to obtain the desired mixture properties.

The baghouse return system on the hot-mix plant used for this project required about 12 to 15 min to stabilize after start-up in the morning. The baghouse was emptied at the end of each day. Plant operators initially believed that the baghouse would be stabilized within 2 to 3 min. The output from the load cell which monitored the amount of baghouse fines returning to the plant indicated that this time was closer to 12 to 15 min.

4.3.2.5 In-Place Air Voids

In-place air voids were a variable in the WesTrack experiment. Control of the in-place air voids was accomplished with nuclear gages calibrated against cores for density, with air voids determined from theoretical maximum specific gravity measurements made on the HMA during the volumetric QC testing. The roller operators and field inspectors controlled the number of passes and the temperature of the HMA at the time the passes were applied. Both static and vibratory modes of compaction were used with the steel wheel rollers (breakdown and finish rolling). A pneumatic roller was used for intermediate rolling. The temperature was recorded at the mid-depth of the 75-mm (3-in.) lift. The temperature at the mid-depth changes at a slower rate than that at the top and bottom of the lift and was believed to be a better indicator for control of the compaction operation.

The roller operators met each morning with the field density crews and inspectors to determine the strategy for obtaining the desired in-place air voids for the day's construction. These meetings were invaluable in establishing the communications necessary to achieve the desired in-place air voids.

The number of roller passes for each compactor, the mode of operation (static and vibratory), and the temperature of each pass were recorded for all test sections. These data need to be summarized and could be used to predict the relative compaction effort required to obtain different air void levels for the fine- and coarse-graded Superpave mixtures.

4.3.2.6 Thickness

Thickness control was difficult at WesTrack. The different mixtures used and the different in-place air voids complicated establishing the proper laydown machine thickness settings for the different materials and sections. The net result was excessive thickness on some of the bottom lifts and excessive total thickness on a few sections. The excess total thickness forced diamond grinding of some sections to achieve the desired 150-mm (6-in.) thickness.

The laydown machine settings and the actual thickness obtained for the different mixes need to be summarized and would prove to be valuable as a guide for both fine- and coarse-graded mixtures with different asphalt contents and in-place air void contents.

4.3.3 Quality Control/Quality Assurance—Replacement Sections

The QA sampling and test plan for the replacement sections is detailed in WesTrack Technical Report UNR-19 (*18*). QA test results can be found in the following reports:

- Asphalt Binder Content — WesTrack Technical Report UNR-16 (*27*)
- Aggregate Gradation — WesTrack Technical Report UNR-23 (*28*)
- Volumetrics — WesTrack Technical Report UNR-10 (*29*)

Considerable additional analysis can be performed on these data sets and the QC data sets from the replacement sections. References 22 through 26 provide an indication of the types of analyses that can be performed with these data sets.

The number of sections and the daily rate at which the sections were placed created problems with obtaining a sufficient number of QC tests to assure that the sections were being placed with the desired properties. A reduction in the number of sections placed per day and an increase in the number of days between the placement of sections would have been beneficial. However, the cost of mobilization and the problems caused by a lack of continuity might create other problems. Overall, the control of the HMA sections was good and the techniques used were considered adequate.

4.3.3.1 Asphalt Binder Content

Calibration of the ignition oven to determine asphalt binder content was a problem on both the original and replacement section construction. Reflux extraction proved to be the best method currently available to determine asphalt binder content and calibrate the ignition oven results.

The asphalt binder content on the replacement sections did not have the range from low to high value desired. Although the plant was set to achieve this range, the test results indicate it was not achieved. Unfortunately, the lack of spread was not apparent from the QC testing during construction.

4.3.3.2 Aggregate Gradation

Changes in the location of the raw material feed to the crushing plant, in crushers, and in the type of products being produced at the plant (HMA versus portland cement concrete aggregates) created problems with the mixture design process as discussed in Chapter 3 of Part I of this report.

Segregation in the stockpiles was also a problem as was sampling of stockpiles to determine gradation uniformity. A minimum of 10 samples, obtained with the use of a front-end loader to provide for a flat sampling area, were necessary for the mixture designs and for determining gradation.

A report comparing stockpile gradations, cold feed gradations, and ignition and reflux gradation needs to be prepared. The variability and mean values from each of these sample locations would provide valuable information for QC purposes to the contracting community.

4.3.3.3 Volumetric Data

Samples for determining QC volumetrics were obtained from behind the paver on the replacement sections and from truck samples for the original construction. QA data were obtained from truck samples for both the original sections and the replacement sections. Comparative analysis of these data sets would be valuable in determining the best sampling location.

4.3.3.4 In-Place Air Voids

The techniques used to obtain the desired air void content on the replacement sections were identical to those used for original construction. Daily meetings and close cooperation were necessary to achieve the desired air voids.

4.3.3.5 Thickness

The lessons learned from the original construction eliminated the need for grinding on the replacement sections.

CHAPTER 5

OPERATIONS

This chapter briefly defines the observations and lessons learned during the operation of the track. For convenience, the topics have been organized under the major headings of trafficking, performance monitoring, and rehabilitation and maintenance activities.

5.1 TRAFFICKING

Over a period of 2½ years, the driverless trucks applied 4.9 million ESALs and covered 1.31 million km (821,000 mi). Observations and lessons learned from vehicle development and trafficking of the WesTrack driverless truck system are summarized in the following sections.

5.1.1 Multiple Failures Will Occur

Redundancy was designed into the WesTrack driverless vehicle system, and there are few potential sites for single-point failures within the system. Where single-point failures are possible—for example, the belt between the stepping motor and steering box—the system is significantly overdesigned. As a result, it was assumed, throughout the design of the system, that two different failures occurring at the same time was improbable.

However, multiple failures did occur at the same time. A steering motor failure and a brake system (air-line) failure simultaneously occurred on one truck, resulting in a "slow-speed track exit," and slight damage to the truck. A second incident was the lockup of the main control computer and almost simultaneous failure of one truck's brake system (regulator valve). This resulted in the crash of two trucks: one stopped (the system functioned properly) and one truck did not. A lesson was learned: a driverless system must be able to control the vehicle in multiple failure scenarios.

5.1.2 Vehicle Wander Is Critical

Both WesTrack and other driverless vehicle systems have proven extremely repeatable in terms of lateral position control. For example, without the wander control built into the driverless vehicle system, the precise repeatability of the truck paths (less than 2-mm (0.08-in.) of variation from center per pass) would reproduce the rain grooves of the tire tread in the pavement surface.

The concentrated wheelpath loading accelerates pavement distress. One concept for an automated highway system is a dedicated vehicle lane, similar to current dedicated high-occupancy-vehicle lanes. Given traffic with extremely repeatable guidance systems, this concentrated loading will accelerate pavement distress and quickly establish rutting or fatigue cracking within the narrow wheel-loading area. Building in and controlling wander is a lesson learned and a consideration for future designs of automated highway systems in the real world and in test tracks.

WesTrack trucks were initially designed to operate "on the wire" (i.e., centered over an embedded guide wire); however to reproduce driver variation, they were later programmed to operate up to 380 mm (15 in.) "off the wire." This capability allowed the track operators to generate a distributed traffic pattern that approached the wander patterns found on typical open highways. Truck wander and the establishment of a different wander algorithm for each truck is an important consideration in future designs. A Gaussian wheelpath distribution with a standard deviation of 100 mm (4 in.) is the minimal recommendation for an automated highway scenario.

5.1.3 Guidance Sensors Can Move

Two lessons were learned about the WesTrack "wire in the road" design. At the time of construction, the wire was installed in a conduit under the asphalt.

The first lesson learned is that it is nearly impossible to keep a conduit or any other sensor device perfectly aligned underneath an asphalt-paving machine. Slight jogs were introduced in the wire during paving and the tightly-controlled trucks followed them. Instead of maintaining a straight path down a tangent section of the track, the trucks executed a series of extremely repeatable left and right steering variations. This was eventually corrected by cutting a groove in the top of the HMA layer and placing a new straight guide wire at the surface.

The other lesson learned is that the wire can, and does, move within the conduit. The direction of WesTrack traffic around the track was always the same—counterclockwise. The wire in the conduit also moved counterclockwise and was displaced approximately 200 mm (8 in.) longitudinally within the first 120,000 km (75,000 mi) of vehicle operation. This tensioned the wire to the point that service loops were pulled tight and the wires eventually broke. This problem was also corrected by moving the wire to the surface.

5.1.4 Slight Lateral Positions Make a Big Difference

When the wire was installed in the spiral that transitions from the straight tangent section to the 18 percent superelevated curve, it was sometimes placed as much as 25 mm (1 in.) laterally from the theoretical centerline on which it should have been placed. This created an undesirable lateral sway when the trucks exited the curve. The lesson learned is that alignment of a curve transition is critical, and the position of a guidance sensor as little as 25 mm (1 in.) left or right of the theoretical path can establish undesirable lateral sway dynamics. Given that sensors can move in HMA, this sensitivity to exact curvature is critical to future designs and installations.

5.1.5 Truck Air-Conditioning Systems Are Not Designed to Operate 24 Hours Per Day

The control computers for the WesTrack trucks were located in the sleeper compartments of the tractors, and the factory-installed vehicle air-conditioning was directed through ducts to keep the computers operating as in an office environment. During the summer, this required the air-conditioning systems to operate up to 22 hours per day, and current, standard truck air-conditioning systems are not designed for such extended, continual operation.

5.1.6 Steering Lash Increases with Gearbox Wear

After some 700,000 km (440,000 mi), the track operators noted the steering lash, the amount of steering wheel play, had increased as the steering gearboxes on the trucks wore. By design, truck steering gear boxes are designed with lash because overly responsive steering on a large truck is not desirable. Steering gearbox wear must be accounted for during steering control design.

5.1.7 Robust Communications Are Necessary

Stable communications systems for longitudinal control are critical. Telemetry communications need to be robust. Loss of communications for as little as 1 sec can cause problems. Of all the redundant subsystems in the WesTrack design, longitudinal control was the most critical.

5.1.8 Steering Tire Selection Is Important for Large Trucks

A natural tendency of radial tires is to go straight. This effect is called self-aligning torque. The higher the self-aligning torque, the greater the tendency to go straight.

Initially, steering tires with relatively high self-aligning torque were selected for the steering axles of the WesTrack trucks. As a result of the increased steering demands on the tires negotiating the curves of the track, the tires showed signs of high wear on their shoulders. After the first 100,000 km (60,000 mi) on each truck, new tires with a lower self-aligning torque were installed. This enabled the trucks to steer with less frequent correction through the curves, and it reduced the demand on the steering motor. Steering tire selection is an important consideration for future vehicle designs.

5.1.9 Vehicle Operations

Four driverless vehicles were operated up to 22 hours per day with an average loading rate of 16 hours per day throughout the testing period. The average operating hours per day included down time for periodic rehabilitation of test sections, for vehicle maintenance, and for unfavorable weather conditions.

Initially, the test track was to be loaded to 10 million ESALs in 2 years. However, because of the failure of some test sections at the early stage of the loading, plans were altered to include the placement of additional experimental sections while still producing fatigue failures in as many sections as possible.

The primary objective of the driverless vehicle integration into the accelerated pavement testing program was to minimize incidents resulting from driver fatigue and drowsiness as a result of monotonous operation of the vehicles for an extended period of time. The automation associated with integration of the driverless vehicles also ensured close monitoring of operating speed.

Two supervisors (a lead electronic technician and a lead mechanic) scheduled and supervised the track loading operation, and maintained the vehicles. Three operators (8 hours per shift, 24 hours per day, 7 days per week) were assigned to the control room. These operators kept records pertinent to the traffic operation. The vehicles were stopped once every 24 hours for refueling and routine inspections. The staging and launching of the trucks was closely monitored to ensure that the actual loading duration was known.

5.1.10 Fuel Economy, Maintenance, and Operating Costs

Although accelerated pavement testing facilities are designed to investigate the performance of pavement materials and structural designs, they also offer the opportunity to collect vehicle operation data, under controlled conditions, for the trucks used to apply the loading. The loading at the WesTrack facility provided a significant amount of data on truck fuel and maintenance costs as a function of pavement smoothness.

5.1.10.1 Pavement Roughness and Its Effects on the Vehicles

The distinct differences in pavement roughness just before and just after pavement rehabilitation presented a unique opportunity to investigate the effects of pavement roughness on fuel consumption, unscheduled maintenance, and other vehicle health-related factors. Relevant data were examined for periods of 8 weeks just before and 7 weeks just after one such rehabilitation to assess the effect of pavement roughness on vehicle health and fuel consumption rate. Measurements of International Roughness Index (IRI) for the tangents of the oval track (*30*) were compared before and after rehabilitation. The measured IRI values showed a 10 percent reduction in IRI after the rehabilitation compared with the IRI just before the rehabilitation. Subjectively, the deterioration of the patched areas caused additional roughness in the form of a pothole-type discrete bump. To document this difference from a vehicle motion resistance perspective, an attempt was made to estimate the rolling resistance of the track using a coast down test (SAE J1263) (*31*). The inside lane of the track (service lane) is relatively smooth compared with the outside lane (test lane). It was assumed the difference in the rolling resistance between the two lanes could be used as an estimator of the relative difference. The coast down test was conducted using a 160 kN (35,900 lb) tractor semi-trailer. The coast down speed range was 32 to 8 km/hr (20 to 5 mi/hr). The result of this limited observation showed that the rolling resistance of the test lane was higher than the inside lane (service lane) by approximately 3 percent.

The power a truck requires at a given time is a function of its speed, its weight, tire/road surface interaction, aerodynamic drag, and grade. The power requirements can be divided into three categories for overcoming: (1) wheel rolling resistance, (2) air drag, and (3) pavement grade.

Rolling resistance is the sum of all resistance impeding the free rolling of the vehicle, so the power required to overcome rolling resistance includes the power required to overcome irregularities in the pavement, flexing of tires, deformation of the road surface, and friction, each of which in turn may depend on the vehicle's gross weight and speed. Given that vehicle gross weight and speed were fixed and that the vehicles were very well maintained throughout the WesTrack experiment, increases in fuel flow rate noted on vehicle performance/health monitoring computers could be directly attributed to increased pavement roughness, that is, increased deterioration of the track led to increased motion resistance to the trucks.

Estimates of rolling resistance for different road conditions are available in the literature (*32*). Table 2 shows typical road rolling resistance (RR) in N per kN (lb per 1,000 lb) of gross combined weight (GCW) for different surface conditions from one such source (*32*). With all other factors held constant, an increase in road rolling resistance from 2.5 N per kN GCW to 5 N per kN (going from a good [smooth] asphalt concrete [AC] pavement to a poor [rough] one) results in a theoretical 100 percent increase in required rolling resistance power (*32*, *33*).

To validate the effect of pavement quality changes on fuel economy, data from two identical WesTrack vehicles, WT-3 and WT-4, were examined for periods just before and after the March 1998 rehabilitation. The fuel consumption rate, fuel temperature, engine torque, and engine speed from the Detroit Diesel Electronic Control (DDEC) units were analyzed, as were other vehicle parameter data. The WesTrack computers recorded this vehicle data twice per second while the trucks were operating. Additionally, fuel use data from the daily inspections and refueling of the WesTrack trucks were analyzed.

The average fuel mileage over an 8-week period before rehabilitation was 1.79 km/L (4.2 mi/gal) for the two trucks. After the rehabilitation, the average fuel mileage over a 7-week period was 1.87 km/L (4.4 mi/gal). This indicates a 4.5 percent improvement in fuel economy as a direct result of the improvement in pavement roughness from the rehabilitation.

Table 3 is a summary of environmental and engine parameter data for the periods just before and just after rehabilitation. The average engine torque was 913 N-m (674 ft-lb) before rehabilitation and 881 N-m (650 ft-lb) after. The average engine speed was 1,456 rev/min. This would correspond to a calculated power of 139 kW and 134 kW (187 and 180 hp) before and after rehabilitation, respectively. Other environmental influences on fuel consumption were evaluated. Temperature effects have been compensated for within this calculation, because the average air temperatures were lower for vehicle operation before the rehabilitation than after. The average wind speeds over the duration before and after the rehabilitation were 5.6 km/hr (3.5 mi/hr) and 7.9 km/hr (4.9 mi/hr), respectively, with consistent average wind direction (Table 3). Given the oval track design (with the trucks traveling both with and against the wind during each circuit of the track), the effects of wind are at least partly negated. Because the average wind speed was higher after rehabilitation than before, the reported improvement in fuel consumption may be less than it would have been if the wind speeds did not differ. Overall, the improvement in fuel consumption would have been slightly greater than 4.5 percent if all of the environmental effects could have been eliminated, that is, if wind speed, temperature, and so forth were the same before and after the rehabilitation.

If the fuel consumption changes noted at WesTrack were extrapolated to a fleet operation of 1,600,000 vehicle-km (1,000,000 vehicle-mi), the savings would be 46,600 L (10,260 gal) of fuel as a result of operating on smooth rather than on rough pavement. From a fleet operator's perspective and an environmental protection standpoint, these savings are substantial.

5.1.10.2 Maintenance Costs

The increase in pavement roughness also increased the frequency of fatigue failures in the truck and trailer components. For example, trailer frames began to fracture (four occurrences) and required reinforcing welds during the time just before pavement rehabilitation. Steering motors and other components loosened more frequently. Figure 4 shows the number of trailer spring failures as a function of the total ESALs applied to the track. Eight of 17 spring failures during the 2½-year loading life occurred in the period 2 months before the March 1998 rehabilitation of the track, resulting in the large increase in the rate of spring failures. Although some 330,000 ESALs were applied to the track sections during the 7 weeks after rehabilitation, compared to the 265,000 in the 8 weeks before, the postrehabilitation trafficking yielded only a single spring failure.

Fatigue and exposure to varying degrees of stress over their lifetimes certainly contributed to the spring failures. Nevertheless, the fact that very few spring failures were observed after rehabilitation is an indicator of severe loading of the trucks by the rough pavement just before rehabilitation.

5.1.10.3 Operation Costs

Figure 5 shows the variation in total truck operating costs over the 2½-year trafficking period. The average cost per kilometer over the 2½ years was approximately $0.86 ($1.38/mi). The equivalent costs incurred during the AASHO road test and the WesTrack project are shown in Table 4.

5.1.11 Safety

Safety, incident, and cost information for the WesTrack project and the AASHO Road Test are shown in Table 5. WesTrack had three incidents, while the AASHO Road Test experienced 141 incidents including two deaths and several injuries. WesTrack trucks traveled 1,310,000 km (840,000 mi) per major incident, while AASHO Road Test trucks traveled some 400,000 km (250,000 mi) per incident. No deaths or injuries were experienced at WesTrack.

5.1.12 Summary

The WesTrack driverless vehicle program was successful and is an operational real-world example of heavy-vehicle driverless operation. It addressed the practical requirements for control system redundancy and for continuous vehicle-safety and vehicle-health monitoring that will be part of practical, intelligent transportation systems. WesTrack operated with four driverless triple-trailer combinations from June 1996 to February 1999. The trucks recorded a total of 1.31 million km (821,000 mi) over that time. Fail-safe controls were implemented, and a practical level of reliability was achieved. A system of continuous vehicle safety monitoring was also demonstrated.

Pavement roughness had a significant impact on fuel consumption of trucks applying loads to WesTrack pavement test sections. Under otherwise identical conditions, trucks used 4.5 percent less fuel per km on smooth (postrehabilitation) than on rough (prerehabilitation) pavement.

Increases in pavement roughness also significantly increased the frequency of fatigue failures of truck and trailer components during the WesTrack loading.

5.2 PERFORMANCE MONITORING

5.2.1 Visual Condition Survey

Visual condition surveys were performed by the same person at 2-week intervals throughout the trafficking of the test track. Having only one person conduct the visual condition survey technique provided a high degree of accuracy and consistency to the data. Variability in the data was noted in some cases between the extent of winter and summer fatigue cracking. This was due to the difficulty of identifying the presence of cracking in the summer months when fatigue cracks have a tendency to heal or visually close up.

The Long-Term Pavement Performance (LTPP) Distress Identification Manual provided the basic definitions and methods for conducting the survey. WesTrack Technical Report NCE-1 (*34*) provides details of the survey procedure and the data reduction techniques used.

Although rutting and fatigue cracking were the distresses of primary importance at WesTrack, differences in raveling and flushing were also noted. The mixtures with low asphalt contents exhibited more raveling than those with higher asphalt binder contents. Those pavements which contained HMA with high asphalt binder contents exhibited more flushing or bleeding than those which contained mixtures with low asphalt contents. The raveling and flushing data have not been analyzed to define these generally observed trends.

5.2.2 Rut Depth

Rut depths were measured with the "Dipstick," the Arizona DOT transverse profile device, and a laser transverse profile device developed by the NATC. With each device, frequency of testing was once every 2 weeks when the track was subjected to traffic. During periods of rapid rutting or fatigue cracking, the frequency was increased.

WesTrack Technical Report NCE-7 (*35*) provides details on the measurement techniques used, the precision of the measuring systems, methods of calculation of the rut depth, and the data for each of the monitoring sessions by section. The Dipstick was used for the first six monitoring sessions. When it was used according to the methods defined by the LTPP program, this device was not adequate to define rut depth on the WesTrack sections. The profile was measured at intervals of 300 mm (12 in.) transversely across the pavement. The profile plotted from the elevation points every 300 mm (12 in.) did not accurately define the rut profiles that existed at WesTrack. The radius of curvature of the ruts at WesTrack was typically very small and the ruts were confined to a relatively short transverse length as compared with the 300-mm (12-in.) elevation point-to-point measuring system.

The Arizona DOT transverse profile device was used as the rut depth measuring device until a transverse laser device was developed. The Arizona DOT device provided a reproduction of the transverse surface profile of the pavement but its accuracy was less than desired and data processing was manual and time-consuming rather than automatic (electronic).

The laser transverse surface profile measuring device proved to be acceptable. Refinements are needed if the device is to be made commercially available for pavement profile measurements.

The use of the three devices created precision problems. Precision of the measurements improved as the project progressed. Ideally, the laser device should have been used from the start of performance measurements. However, the WesTrack team initially relied on the standardized LTPP performance measurement techniques.

Rut depths can be defined from surface profile measurements by a number of methods. Standardization of rut depth definitions is needed for LTPP as well as for projects like WesTrack. In addition, the performance equations should be developed using rut depths as defined by different methods.

5.2.3 Fatigue Cracking

The presence of fatigue cracking was recorded during the visual condition survey at a frequency of once every 2 weeks when the track was subjected to traffic. During periods of rapid development of fatigue cracking, the frequency was increased. WesTrack Technical Report NCE-1 (*34*) provides details on the measurement technique used, the precision of the measuring system, and methods of calculating the amount of fatigue cracking.

Differences in accumulation of fatigue cracking with ESALs for a selected section was primarily due to the uncertainty inherent in the visual condition survey method. During the summer months, it was often difficult to see fatigue cracking.

A review of fatigue crack development indicated that the majority of the fatigue cracking occurred during the winter months when temperatures were relatively low and crack propagation was relatively rapid. Possible relationships between pavement temperatures and the occurrence of fatigue cracking need additional analysis. In addition, the difference in the development of fatigue cracking in the left wheelpath versus the right wheelpath on many of the sections needs additional analysis. The left side of the truck had slightly more weight than the right side of the truck because of the truck components, load shifting on the trucks, and pavement cross-slope. Deflection measurements made in both wheelpaths could also be used in that analysis.

5.2.4 Longitudinal Profile

Surface longitudinal profile data for the WesTrack project were collected using the Law Profilometer and LTPP-defined methods. The surface longitudinal profile was determined approximately once per month. During periods of rapid development of distress, the frequency was increased. WesTrack Technical Report NCE-3 (*36*) provides details on the measurement techniques used, data reduction techniques, precision estimates, and QC/QA analysis.

Longitudinal profile data shows that differences in roughness can exist between the two wheelpaths. Some of this difference was associated with fatigue cracking developing in the left wheelpath at a faster rate than in the right wheelpath. Relationships between roughness at any time and initial roughness, fatigue cracking, rutting, and other distresses need further analysis.

5.2.5 Subsurface Transverse Profile

Subsurface transverse profile measurements were made with a U.S. Forest Service liquid level device. These profiles were measured approximately once per month when the track was subjected to trafficking. The measurement of the transverse profile at the interface between the engineered fill and base course was not possible for many of the sections because the hose closed during construction and the liquid level measuring device could not move through the hose.

The extensive data set collected from the subsurface transverse profile measurements has been reduced, but little analysis has been performed. Comparisons between surface transverse profiles and subsurface transverse profiles need to be made for each section over the life of the facility. Preliminary analysis indicates that the rutting in the surface was largely confined to the HMA layer. This was confirmed visually when post mortem trenching of rutted sections was completed.

Rutting was noted at the interface between the HMA and the base course only after fatigue cracking occurred and the pavement sheared at the edges of the wheelpath. The hoses used were relatively stiff and could contribute to inaccurate measurement when small deformations were experienced in the pavement layers.

5.2.6 Deflection

FWD data were obtained at several locations along each test section at monthly intervals. The information was extensively analyzed and has been used in the development of the performance models. All techniques used to reduce the data to supply stiffness values for the pavement layers experienced difficulty. Improved techniques are needed if FWD information is to be used with confidence in engineering analysis of pavement sections.

5.2.7 Friction

Friction was measured on WesTrack pavements with a locked wheel skid trailer nine times during the trafficking of the track; however, the measurements have not been analyzed to date.

5.2.8 Post Mortem Sampling and Testing

Post mortem sampling and testing was performed on all sections placed at WesTrack. The procedures used and examples of data from this post mortem sampling and testing effort can be found in WesTrack Technical Report NCE-5 (*37*). The post mortem sampling and testing program indicates that the rutting in the WesTrack sections was largely confined to the HMA material.

Although the data have been analyzed, a greatly expanded analysis program could be performed. Cone penetration values, in-place density of the base course, and other collected data should be used to establish relationships with performance of the pavements.

5.3 REHABILITATION AND MAINTENANCE ACTIVITIES

Pavement rehabilitation and maintenance activities were carried out during the trafficking of WesTrack. The initiation of the rehabilitation and maintenance activities was based on the section reaching a failed condition or the track becoming unsafe for truck operation.

Several rehabilitation and maintenance operations performed at WesTrack were very successful. Pavement sections that were rutted during the summer months of trafficking were repaired by one of three techniques: (1) full lane width, partial-depth mill-and-fill, (2) wheel track, full-depth mill-and-fill, and (3) surface milling without replacement of HMA.

Removal and replacement of the entire test lane width to a depth of 50 mm (2 in.) was successful. The procedure was performed in fall 1996 and carried traffic to May 1997. During the cooler months, rutting did not reoccur even though only 50 mm (2 in.) of the 150-mm (6-in.) lift of HMA was removed and replaced. The repair of rutted pavement in the fall with a relatively thin mill-and-fill operation or overlay can successfully repair a pavement for a period of time to allow for the replacement of the section in the late spring when weather conditions are more favorable for the placement of HMA. The performance of this relatively thin lift was excellent considering the high traffic volumes placed on the pavement at this accelerated test track facility.

A full depth repair of the wheelpaths in one section was performed during the early winter and was successful. This repair technique carried the accelerated traffic through the winter months until May when the entire section was replaced. The width of wheel track repair should be wide enough to allow for the smaller rollers to enter the trench sections created by the mill operation. In-place air voids must be controlled to have a successful repair.

The wheelpaths in several sections were milled approximately 25 mm (1 in.) in depth in fall 1997 to remove rutting of the HMA. This repair technique was successful in preventing rutting during the cooler winter and spring months. When high temperatures occurred during the summer, the HMA once again rutted. The use of full width milling to repair rutting types of failures in the fall of the year to allow for a more permanent repair in the spring is viable as indicated by the performance of the WesTrack pavement sections.

Permanent patches of HMA were placed full depth at the track. Patches placed in a “T” configuration as shown in Figure 112 of Part I of this report were successful. Patches with straight edges, the entire 150-mm (6-in.) depth of the HMA, were not successful due to pumping and subsequent failure. The heavy, accelerated traffic on WesTrack afforded a limited opportunity to study performance of patching techniques and materials.

Cold mix patching materials were placed at WesTrack and were largely unsuccessful. A special patching material available locally did not perform for other than short periods of time at WesTrack. A proprietary cold patching material performed during the cooler winter months, but rutted at the onset of warm weather under the heavy truck traffic.

Diamond grinding proved to be an effective method of providing smoothness after construction and after patch placement. Grinding should be considered as a technique to restore smoothness to a pavement after patching.

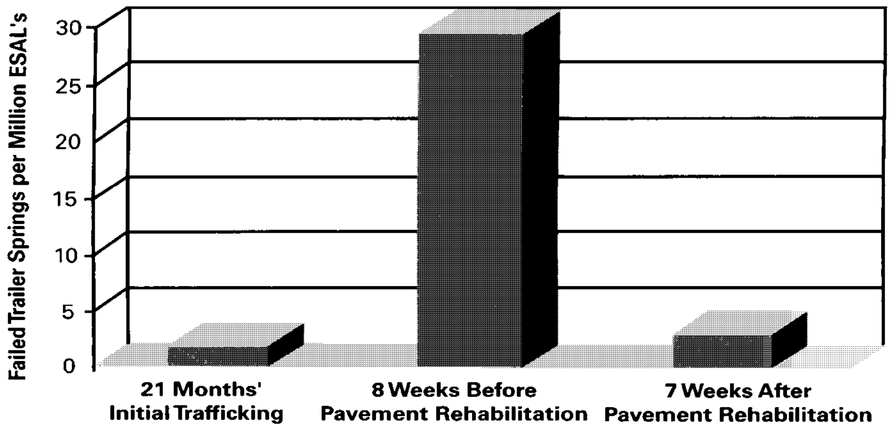
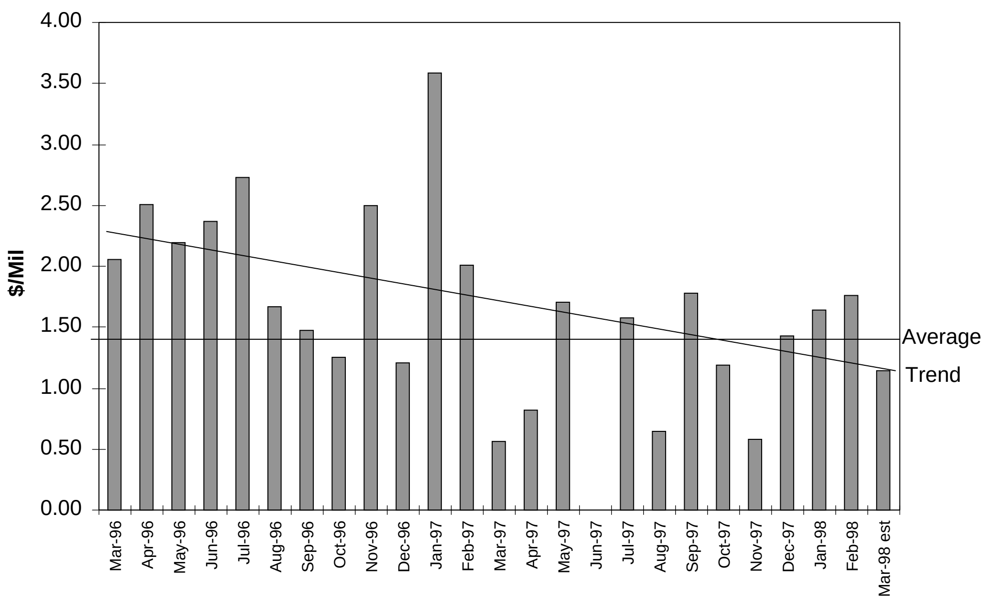


Figure 4. Example of the effect of pavement condition on truck health.



$/km = 0.625 $/mi

Figure 5. Total vehicle operating cost per unit distance by month during trafficking.

TABLE 2 Typical values for asphalt concrete surface rolling resistance (*32*)

Asphalt Road Condition	RR, N per kN GCW	RR, lb per 1,000 lb GCW
good (smooth)	2.7	12
fair	3.8	17
poor (rough)	5	22

TABLE 3 Summary of environmental and engine parameter data before and after rehabilitation

	Before Rehab. 1/5/98 - 3/1/98		After Rehab. 3/13/98 - 5/6/98	
Number of kilometers	38,970		48,942	
Environmental	**Avg.**	**Std. Dev.**	**Avg.**	**Std. Dev.**
Ambient temperature (°C)[1]	2.3	5.2	6.5	5.6
Maximum relative humidity (%)	75.8	20.7	64.8	22.4
Minimum relative humidity (%)	66.8	22.2	54.3	22.0
Wind speed (km/hr)[2]	5.6	5.5	7.9	6.1
Engine parameters				
Fuel rate (liters/hr)[3]	32.2	4.5	31.0	4.2
Output torque (N-m)[4]	913.1	138.8	881.1	131.5
Engine RPM	1456.1	6.4	1455.8	5.6
Engine load (%)	51.6	6.5	50.0	6.2
Throttle (%)	59.4	4.2	58.4	4.0
Fuel temperature (EC)	35.6	0.8	40.2	0.6
Calculated power (kW)[5]	139.3	21.2	134.4	20.1

[1] °F = 1.8°C + 32
[2] mi/h = 0.625 km/h
[3] gal/h = 0.264 L/h
[4] ft-1b = 0.738 N-m
[5] hp = 1.34 kW

TABLE 4 Average operating costs per mile

Test Facility		Total Truck Operating Costs	
		Dollars per Vehicle-km	Dollars per Vehicle-mi
WesTrack		0.86	1.38
AASHO Road Test	1960 $	0.20	0.32
	1997 $	1.06	1.70

TABLE 5 Safety incidents and cost incurred for WesTrack and AASHO road test

	WesTrack	AASHO
No. of incidents	3	141
Cost	$250,000	$53,814 (1960) $289,363 (1997)*
km per incident[1]	437,000	199,800
km per major incident[1]	1,310,000**	413,800 including two deaths

*Cost basis year, assumes 4-1/2 % average inflation rate over 38 years.
**Only one major accident occurred.

[1] 1 mi = 1.61 km

CHAPTER 6

MATERIALS CHARACTERIZATION AND PERFORMANCE MODELS

6.1 MATERIALS CHARACTERIZATION

The materials characterization program was initially defined and then adjusted during the course of the project. Superpave performance tests were to be used for materials characterization. Unfortunately, at the time the WesTrack team was preparing to conduct the materials characterization testing, the Superpave performance tests and the models used with these test results to predict permanent deformation, fatigue cracking, and thermal cracking had been judged unacceptable in their present form by an FHWA research effort.

SHRP-developed test methods were then used to characterize HMA material properties for prediction of permanent deformation, fatigue cracking, and thermal cracking. The simple shear tester (SST) operated in the constant height. Repeated load mode was used after the fact to characterize the mixtures for permanent deformation prediction. The bending beam fatigue test apparatus was used to characterize the mixtures for fatigue crack prediction, and the thermal stress restrained specimen test (TSRST) was used to predict thermal cracking.

Water sensitivity of the WesTrack mixtures was determined by use of AASHTO T 283 or the modified Lottman test. A freeze-thaw cycle was used as required by the test method for all testing.

The original test plans for characterization of the HMA were altered several times during the conduct of the WesTrack project to provide improved focus to the project, to respond to budget constraints, and to consider schedules. Initially, the test program was established to test laboratory-mixed/laboratory-compacted (LMLC), field-mixed/laboratory-compacted (FMLC), and field-mixed/field-compacted (FMFC) samples. LMLC samples are both mixed and compacted in the laboratory and are typically used for mixture design purposes. The laboratory mixing and compaction processes are intended to simulate field mixing and field compaction processes.

FMLC samples are those samples prepared with field-mixed HMA using laboratory-compaction methods. Samples prepared with this methodology are typically used for QC/QA purposes. The laboratory-compaction process is intended to simulate field-compaction processes.

FMFC samples are typically obtained by coring or removing slabs of pavement. The samples are mixed and compacted with field equipment during construction and represent the actual pavement material in place. The laboratory mixture characterization program placed primary emphasis on testing FMFC samples because these mixtures represented the HMA at WesTrack. It was believed that the best correlations between material properties and field performance of the mixtures could be obtained with the FMFC samples.

FMFC samples were obtained immediately after construction, after approximately 12 months of trafficking, and at the end of trafficking (post mortem). Testing was, therefore, performed on HMA from selected sections before and after aging and trafficking.

The second most important group was the LMLC samples, because they represent the conventional method used for preparing mixture design samples. A reduced testing program was performed on this group of samples.

Some testing was performed on FMLC samples. This sample group will become more important to the public agencies and contractors as acceptance of the mixture becomes more dependent on HMA properties and less dependent on asphalt binder contents and aggregate gradations. Differences between laboratory- and field-plant-produced HMA are also being recognized as being significant.

Observations relative to the materials characterization program are presented in the following subsections. Permanent deformation, fatigue, thermal cracking, water sensitivity, theoretical maximum specific gravity, resilient modulus, tensile strength, and recovered asphalt binder content testing are discussed.

6.1.1 Permanent Deformation

The SHRP-developed SST was used to characterize the WesTrack HMA mixtures for prediction of permanent deformation. The major portion of the testing characterized FMFC samples. Samples were obtained immediately after construction, after approximately 12 months, and at the completion of trafficking. An additional laboratory program was conducted at North Carolina State University to determine the influence of aggregate gradation on the permanent deformation properties of an HMA. Those samples were prepared by laboratory-mixing and laboratory-rolling-wheel-compaction techniques.

The SST data have been used to develop the level 2 performance models to predict permanent deformation. Differences between samples prepared by the three techniques identified above have not been defined to date. Detailed permanent deformation test results are available in WesTrack Technical Report UCB-1 (*38*) and the WesTrack database (Part III of this report).

Although the permanent deformation testing was performed over a temperature range for some of the mixtures, additional testing at high temperatures may be informative. The WesTrack rutting occurred when the pavement reached a critical temperature of approximately 60°C to 63°C (140°F to 145°F) at a depth of approximately 20 mm (0.8 in.). Developing test equipment that allows the mixtures to be characterized at these temperatures should be considered.

6.1.2 Fatigue

The SHRP-developed beam fatigue test was used to characterize the WesTrack HMA mixtures for prediction of fatigue cracking. The major portion of the testing was conducted with FMFC samples. Samples were obtained immediately after construction, after approximately 12 months, and at the completion of trafficking. A limited laboratory test program was performed on LMLC samples.

These test results were used to develop the level 2 performance models to predict fatigue cracking. Differences between the samples prepared by these three techniques have not been defined to date. Detailed fatigue test results are available in WesTrack Technical Report UCB-1 (*38*) and the WesTrack database.

Although the fatigue testing was performed over a temperature range for some of the mixtures, additional testing is needed to study crack propagation and fatigue behavior. Most of the WesTrack fatigue cracking first became visible at the surface of the pavement during the winter months.

6.1.3 Thermal Cracking

The SHRP-developed TSRST and the indirect tensile creep and strength test were used in the WesTrack project to characterize mixtures for thermal cracking potential. LMLC, FMLC, and FMFC (cores) were used in the testing program. FMFC samples were obtained immediately after construction, at 12 months, and at the end of the trafficking.

Because WesTrack did not experience thermal cracking during the 2½-year trafficking period and because WesTrack used two asphalts of the same performance grade in the original and replacement sections, performance models have not been developed from the WesTrack data. The data analysis performed with MnRoad information suggests that the TSRST testing approach provides reasonable estimates of cold temperature cracking.

Thermal cracking models have, therefore, not been used in the PRS development on the WesTrack model. Asphalt binder selection is used to prevent thermal cracking in the performance-related Guide Specification in Appendix C of Part II of this report. Detailed thermal cracking test data information can be found in WesTrack Technical Report OSU-1 (*39*) and the WesTrack database.

6.1.4 Water Sensitivity

Water sensitivity testing was performed on FMFC core samples obtained immediately after construction, after approximately 12 months, and at the end of the trafficking period. The AASHTO T 283 test procedure was used to evaluate water sensitivity.

Some of the test results indicate that water sensitivity could be a problem with the WesTrack materials, but no evidence of stripping or water damage was noted when examining the cores, slabs, and post mortem trench sections. WesTrack only receives about 100 mm (4 in.) of precipitation annually, but stripping of asphalt from aggregates is not uncommon in this area of the United States. Correlations between laboratory test results and field performance of mixtures relative to water sensitivity needs definition. Detailed water sensitivity test data are available in WesTrack Technical Reports OSU-2 (*40*) and UNR-26 (*41*).

The WesTrack-developed water sensitivity acceptance criteria will initially be based on the use of AASHTO T 283 on LMLC mixtures. An improved water sensitivity test that relates to field performance is needed.

6.1.5 Theoretical Maximum Specific Gravity

An extensive laboratory testing program was performed on replacement section HMA mixtures to determine if mixture aging prior to the determination of the theoretical maximum specific gravity would affect the test results and help explain the differences between mixture design volumetrics (LMLC) and FMLC sample volumetrics. The laboratory-aged samples correlated very well with those of the field-aged samples. Comparisons of laboratory and field data show that the Superpave short-term oven aging procedure induced aging very similar to the aging which occurred during construction in terms of theoretical maximum specific gravity and other related volumetric properties.

Additional analysis of the data is needed. WesTrack Technical Report UNR-25 (*42*) contains the detailed information from this study.

6.1.6 Resilient Modulus and Tensile Strength

An extensive laboratory testing program was conducted on WesTrack mixtures to define the resilient modulus and tensile strength properties. This study was conducted as part of the water sensitivity study and is reported in WesTrack Technical Report UNR-26 (*41*). The resilient modulus was determined at different pavement ages on core samples from the two lifts.

Additional analysis of the data to examine the influence of asphalt binder content, aggregate gradation, and in-place air void content is needed. Reference 43 also contains the resilient modulus and tensile strength data.

6.1.7 Recovered Asphalt Binder Properties

Asphalt binder was extracted and recovered from core samples of HMA and its properties were determined. These data showed the typical trends of an increase in stiffness with age. In general, the binder in the coarse-graded mixture hardened at a faster rate than in the comparable fine-graded mixtures. This difference in hardening rate is partially a result of the construction hardening and most likely a result of higher air and water permeability associated with coarse-graded mixtures as compared with fine-graded mixtures.

6.2 PERFORMANCE MODELS

Figure 6 provides a summary of the performance models developed as part of the WesTrack effort. Level 1 and level 2 models have been developed. Performance prediction parameters in level 1 models are those that are conventionally obtained by public agencies (asphalt binder content, gradation, in-place air voids, and ESALs). Performance prediction parameters in level 2 models are obtained from performance tests such as the SHRP-developed SST and the bending beam fatigue machine, as well as some of the parameters conventionally obtained by public agencies. Structural pavement analysis programs are typically a part of the level 2 models and are used to calculate stresses and strains in the pavement sections.

Level 1 permanent deformation models are further subdivided into level 1A and level 1B. The level 1A models are direct regressions and provide performance prediction equations that are applicable to WesTrack mixtures, temperatures, and traffic. The level 1B models are applicable to WesTrack mixtures (coarse- and fine-graded Superpave), but can consider other traffic conditions and climates (temperature).

The level 2 permanent deformation models are also divided into level 2A and level 2B models. The level 2A models are mostly applicable to WesTrack-type mixtures, but can be used in different temperature and traffic conditions other than WesTrack. The level 2 models use mixture performance tests as their primary parameters for performance prediction.

The level 2B models are suitable for all types of mixtures and can be used for a variety of climates and traffic considerations. Laboratory characterization tests and analysis must be performed on local mixtures to define the parameters for use with the level 2B models.

The level 1A models can be used by almost all public agencies at present because the test parameters used for prediction of performance and hence pay factors are commonly performed. The level 1B and level 2 models use a mechanistic approach with mixture performance tests and mechanistic analysis to provide the performance models. The level 1B and level 2 models have application to a wider range of HMA types, climates, and traffic.

Additional model development is likely to take place after the completion of the WesTrack project. Different groupings of the data sets, new tests or test parameters, different or new mechanistic approaches for predicting stresses and strains, and so forth should be investigated in these future performance prediction modeling efforts.

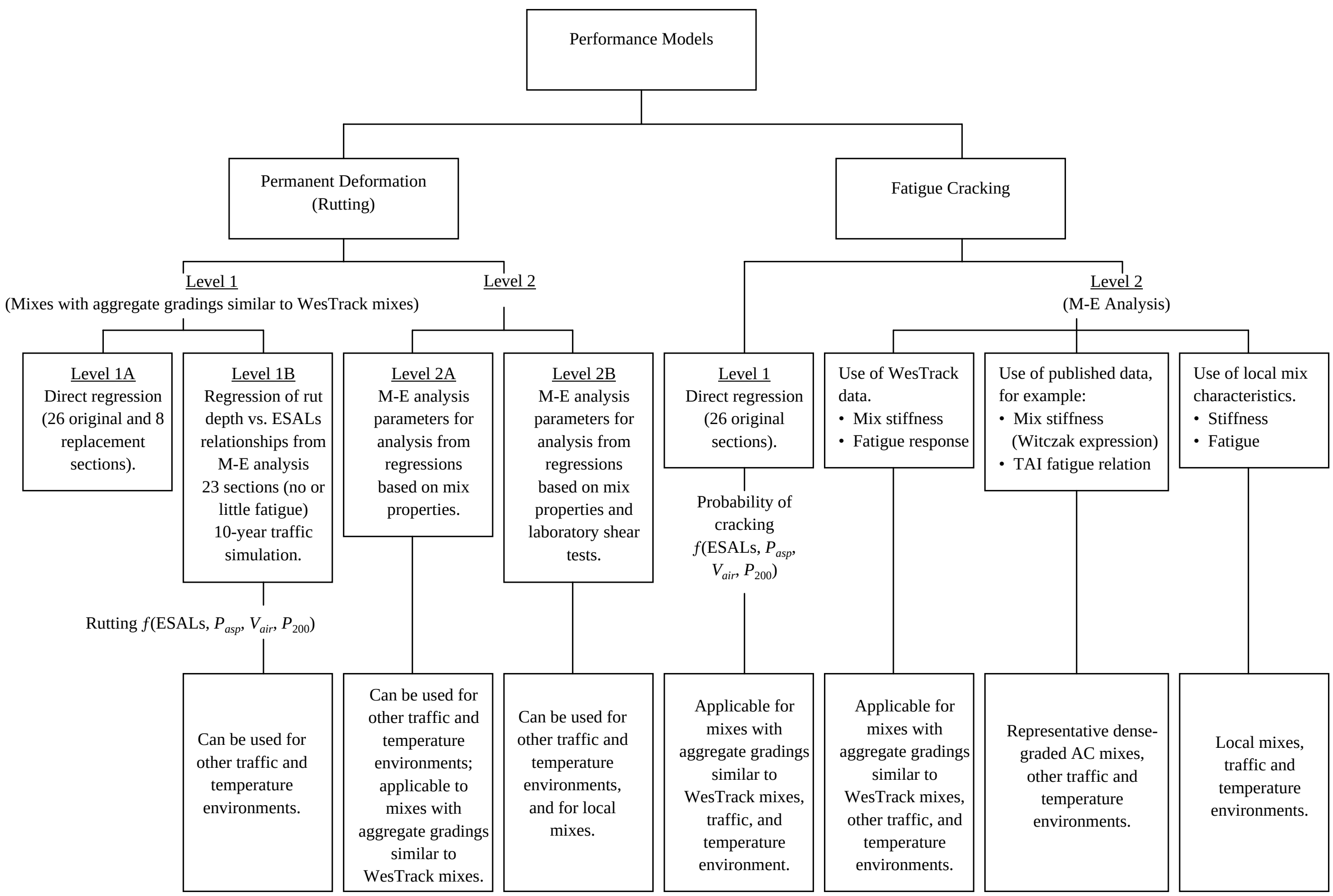


Figure 6. Performance model framework.

CHAPTER 7

REPORTS AND PUBLIC INFORMATION ACTIVITIES

7.1 REPORTS

The WesTrack team has produced a four-part report, WesTrack technical reports, technical papers and articles, and graduate student theses. All of these types of reports have performed a useful function and are an appropriate mix of documentation.

One of the primary lessons learned from this project has been the timing of producing the documentation. The project was not planned or staffed to produce reports as the project was conducted. Although some technical reports were produced during the conduct of the project, the majority of the reports were developed during the last 6 months of the project. Staffing, budgets, and scheduling should be established at the start of projects of this magnitude to produce reports as the project progresses.

The depth of analysis to support the technical reports was also limited by budget and time restrictions. A considerable number of full-time staff engineers need to be assigned to these types of projects. This will not only allow for the needed continuity, but also provide for more in-depth analysis and report preparation as the project progresses.

The majority of the information collected on the WesTrack project has not been published in technical archived publications. Emphasis should be placed on preparing these types of technical papers in the future. Future projects of this size and scope should also consider the preparation of these types of papers and reports as a budgeted work item.

7.2 PUBLIC INFORMATION ACTIVITIES

The video prepared for WesTrack was an information type of video and served a useful purpose, as did meetings and briefings on the project. An additional video should be prepared that summarizes the technical findings of the WesTrack project.

Numerous tours of the track facility and the open house for WesTrack were also useful. More than 1,000 visitors toured the WesTrack facilities. Future projects should consider this as an expanded budget item.

More than 70 presentations were made throughout the United States on WesTrack. This number of presentations could have been increased with the formation of a speaker's bureau for the project. An additional round of presentations at conferences and workshops is now needed to provide the results of WesTrack to a wide audience.

7.3 FUTURE ACTIVITIES

NCHRP Project 9-22, "Beta Testing and Validation of HMA PRS," is in progress. This project will allow for refinements in the PRS and software, as well as provide support for implementation of the findings of WesTrack on a limited basis in state departments of transportation.

No additional testing is presently scheduled at WesTrack. The facility should be marketed and used as an accelerated testing facility for pavements and vehicles and vehicle/pavement interaction studies. Seed money is needed for this marketing effort.

ABBREVIATIONS

DDEC	Detroit Diesel Electronic Control
DOT	Department of Transportation
ESAL	Equivalent Single-Axle Load
FHWA	Federal Highway Administration
FMFC	Field-Mixed/Field-Compacted
FMLC	Field-Mixed/Laboratory-Compacted
FWD	Falling Weight Deflectometer
GCW	Gross Combined Weight
HLA	Harding Lawson and Associates
HMA	Hot-Mix Asphalt
IRI	International Roughness Index
LMLC	Laboratory-Mixed/Laboratory-Compacted
LTPP	Long-Term Pavement Performance
MRL	Materials Reference Library
NATC	Nevada Automotive Test Center
NCE	Nichols Consulting Engineers
NCHRP	National Cooperative Highway Research Program
OSU	Oregon State University
PG	Performance-Graded
PRS	Performance-Related Specification
QA	Quality Assurance
QC	Quality Control
QC/QA	Quality Control/Quality Assurance
SHRP	Strategic Highway Research Program
SST	Simple Shear Tester
TSRST	Thermal Stress Restrained Specimen Test
UCB	University of California, Berkeley
UNR	University of Nevada, Reno

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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