Horizontal Curve Design
To Prevent the Rollover of Heavy Trucks

By

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PURPOSE

The purpose of this paper is to provide highway designers with information necessary to check horizontal curves to prevent rollover of heavy commercial vehicles. Heavy vehicles are those with five axles on the ground, such as tractor trailers, gasoline tanker trucks, etc.

It is possible for some types of heavy trucks, with certain loading conditions to rollover while traveling at speeds below the design speed of the curve.

Heavy truck rollovers account for only three-percent of all crashes of heavy trucks. The fatalities associated with rollover crashes account for 52-percent of all fatal truck crashes. (1) The cost of a rollover that resulted in properly damage only was almost two hundred thousand dollars. If a fatality occurred the cost was more than one million dollars. (2)

The rollover of heavy trucks has generally not been a consideration when designing horizontal curves. A Policy on the Geometric Design of Highways and Streets, (AASHTO Greenbook) (3) does not address truck rollover. Twenty-five State Departments of Transportation, Highway Design Manuals were reviewed and only one, New York (4) has a section on the design of horizontal curves to prevent heavy truck rollover.

The Institute of Transportation Engineers, in their publication, “Geometric Design and Operational Considerations for Trucks” (5), does take into account heavy truck rollover, as a factor in the design of horizontal curves.

HORIZONTAL CURVES

When a vehicle travels along a curved roadway or makes a turn, centrifugal and centripetal forces act on it. The amount of the centrifugal force, or lateral acceleration is generated by the vehicles speed and degree of curvature (sharpness). The centripetal force, which is also a function of the vehicle speed and sharpness of the curve that must counteract the centrifugal force comes from the friction developed between the vehicle’s tires and the roadway pavement. The superelevation of the roadway provides an
additional retarding effect on the lateral acceleration, and therefore lessens the side friction demand. Both forces act through the center of gravity of the vehicle.

The “Simplified Curve” equation from Ref. (3), which is used to determine the side friction factor is:

\[ f = \frac{V^2}{15R} - e \]  

\[ f = \text{Side friction factor (g's)} \]
\[ V = \text{Design speed (mph)} \]
\[ R = \text{Radius (ft.)} \]
\[ e = \text{Superelevation (ft./ft.)} \]
In highway design the side friction factor is considered to be equivalent to the lateral acceleration. The angular difference, created by the superelevation, between the lines of action of the two forces acting on the vehicle is small, and therefore is not considered relevant in highway curve design.

The equation to determine the lateral acceleration which is equivalent to the “simplified curve” equation is:

\[ a = \frac{v^2}{15R} - e \]  

(2)

a=Lateral acceleration (g's)

To convert equations (1) and (2) to the metric system, replace the 15 with 127, meters for feet and km/h for mph.

Side friction factors values used in highway design are based on providing a feeling of comfort to the driver and occupants of passenger cars. These values may not be satisfactory for heavy trucks, especially at low design speeds.

The center of gravity of a loaded heavy truck is much higher than that of a passenger car. The centrifugal force acting on a truck produces an overturning moment before the truck would begin to skid. The opposite is true of passenger cars, they will skid long before they overturn.
ROLLOVER THRESHOLD

The University of Michigan Transportation Research Institute, (UMTRI) has been researching how highway geometry relates to the characteristics of heavy trucks, since 1970. Their research has yielded peak values of lateral acceleration a heavy truck can withstand. Values greater then these peak values will cause the truck to rollover.

The equation developed by UMTRI to determine this peak value is:

\[
a = \frac{RT - SM}{1.15}
\]

(3)

RT = The rollover threshold value for a specific truck and loading condition.

SM = UMTRI arbitrarily set the Safety Margin at 0.10 g's, which would cover the contingency of a heavy truck going 40 mph on a curve with a design speed of 30 mph.

1.15 provides a tolerance corresponding to the level of steering fluctuations, which have been measured in tests of the normal driving of a tractor trailer through interchange ramp curves.

Since lateral acceleration is equivalent to side friction factor, the value of “a” determined in equation (3) should be substituted for “f” in equation (1).

SUPERELEVATION TRANSITION METHODS

For superelevation, most State D.O.T.s use the two-thirds/one-third rule, that is, two-thirds of the transition from the normal cross slope (after any crown has been removed) to full superelevation, is placed on the tangent prior to the beginning of the curve (PC) and the remaining one-third is accomplished on the curve. There are some D.O.T.s that use 80-percent of the transition on the tangent and 20-percent on the curve. If a spiral curve is used, the full superelevation will be at the beginning of the circular curve (S.C.). Placing all of the transition on the tangent, so there would be full superelevation at the P.C. is not recommended by AASHTO.
Studies of driver characteristics have shown that most drivers enter curves at speeds above the posted speed, and they begin accelerating as they approach the end of the curve. Therefore the rollover of heavy trucks should be checked at the beginning of the circular curve, the P.C. and at the end of the curve, the P.T., since these locations will have less than the full amount of the required superelevation.

- **ROLLOVER THRESHOLD VALUES**

Rollover Threshold Values for a tractor with a trailer 46-feet long (from Ref. 6), for double trailers, see page 22 of Ref. (6)

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>Gross Vehicle Weight (lbs.)</th>
<th>Trailer Width (ft.)</th>
<th>Tractor Width (ft.)</th>
<th>Rollover Threshold (g’s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium Density Freight (31 lbs./cu. ft.)</td>
<td>80,000</td>
<td>8.0</td>
<td>8.0</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>80,000</td>
<td>8.5</td>
<td>8.0</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>80,000</td>
<td>8.5</td>
<td>8.5</td>
<td>0.41</td>
</tr>
<tr>
<td>Low Density Freight (16.5 lbs./cu. ft.)</td>
<td>77,000</td>
<td>8.0</td>
<td>8.0</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>80,000</td>
<td>8.5</td>
<td>8.0</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>80,000</td>
<td>8.5</td>
<td>8.5</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Rollover Threshold Values from Ref. (7)
- Gasoline Tanker – 0.32 g’s
  Gross Vehicle Weight of 80,000 lbs.

- Cryogenic (circular) Tanker, - 0.26 g’s
  Gross Vehicle Weight of 80,000 lbs.

- Typical Freight Load - 0.28 g’s
  Less than Total Load
  Gross Vehicle Weight of 73,000 lbs.

- The New York D.O.T. uses a rollover threshold value of 0.36 g’s for tractor trailers with a gross vehicle weight of 80,000 lbs. or more. For high center of gravity tanker trucks they use 0.22 g’s. (Ref 3)
• The Institute of Transportation Engineers, in Ref. (4), uses the rollover threshold values from Ref. (7)

Equation (3) and the rollover threshold values from Ref. (1) were incorporated into an automatic warning system to prevent truck rollover on curved ramps, installed on the Capital Beltway in Maryland and Virginia Ref. (8).

EXAMPLE

A ramp is to be designed for a design speed of 45 mph, a superelevation rate of 0.08 ft./ft. The minimum allowable radius is 587 feet, and the selected rollover threshold is 0.28.

\[
\begin{align*}
    a &= \frac{RT - SM}{1.15} \\
    &= \frac{0.28 - 0.10}{1.15} \\
    &= 0.16
\end{align*}
\]

Using the two thirds – one third method of superelevation transition, the superelevation at the P.C. would be 0.06, check the rollover speed at the P.C., and using “a” for the required side friction factor.

\[
V = \sqrt{15R(e + f)}
\]

\[
V = \sqrt{15 \times 587(0.06 + 0.16)}
\]

\[
V = 44 \text{mph}
\]

If 80-percent of the superelevation is placed on the tangent and 20-percent in the curve, the superelevation rate at the P.C. would be 0.07 and the rollover speed at the P.C. would be 45 mph.

Another solution would be to determine the radius required to comply with the design speed of 45 mph, with the rollover threshold of 0.28
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\[ R = \frac{V^2}{15(e + f)} \]

\[ R = \frac{45^2}{15(0.06 + 0.16)} \]

\[ R = 614' \]

Using the 614 feet radius combined with the 80-percent of the superelevation transition on the tangent would yield a rollover speed of 46 mph. So, if there is available right-of-way for a radius of 614 feet and sufficient tangent length available to use, the 80/20 transition method, that would be a better solution.

SELECTING A ROLLOVER THRESHOLD VALUE

Selecting a rollover threshold value of 0.28 would provide for a tractor trailer that is 8.5 feet wide with low density freight. It would also cover a “Typical Freight Load” and gasoline tanker trucks. This rollover threshold value would also be the most conservative. From Table 2 it can be seen that the 614 foot radius at speeds of 45 mph or less would have to be increased; only 59-feet at 30 mph and 27-feet for a design speed of 45 mph. If increasing the radius did not increase right-of-way requirements then the 0.28 value would be a good choice.

As in all highway design the driver should not be surprised, this is especially true for truck drivers, since their vehicle is more difficult to control then a passenger car. The following highway locations where the designer should be aware of the needs of heavy trucks are:

- Exit and Entrance Ramps
- Loop Ramps
- Compound Curves
- Sharp curves at the end of steep down grades
- Reverse Curves
- Broken Back Curves
- All locations where minimum curve criteria is used, along with low design speeds

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### TABLE 1

**ROLLOVER SPEEDS FOR SIX-PERCENT SUPERELEVATION AT THE P.C.**

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Minimum Radius (ft.)</th>
<th>Super-elevation at the PC</th>
<th>Rollover Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>RT = 0.28</td>
</tr>
<tr>
<td>30</td>
<td>214</td>
<td>0.06</td>
<td>26</td>
</tr>
<tr>
<td>35</td>
<td>314</td>
<td>0.06</td>
<td>32</td>
</tr>
<tr>
<td>40</td>
<td>444</td>
<td>0.06</td>
<td>38</td>
</tr>
<tr>
<td>45</td>
<td>587</td>
<td>0.06</td>
<td>44</td>
</tr>
<tr>
<td>50</td>
<td>758</td>
<td>0.06</td>
<td>50</td>
</tr>
</tbody>
</table>

### TABLE 2

**MINIMUM RADIi FOR SELECTED ROLLOVER THRESHOLD VALUES**

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Super-elevation (ft./ft.)</th>
<th>Super-elevation at the PC</th>
<th>AASHTO Min. Radius (ft.)</th>
<th>Radius Required for Specific Rollover Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RT = 0.28 (g's)</td>
</tr>
<tr>
<td>30</td>
<td>0.08</td>
<td>0.06</td>
<td>214</td>
<td>277</td>
</tr>
<tr>
<td>35</td>
<td>0.08</td>
<td>0.06</td>
<td>314</td>
<td>376</td>
</tr>
<tr>
<td>40</td>
<td>0.08</td>
<td>0.06</td>
<td>444</td>
<td>492</td>
</tr>
<tr>
<td>45</td>
<td>0.08</td>
<td>0.06</td>
<td>587</td>
<td>622</td>
</tr>
<tr>
<td>50</td>
<td>0.08</td>
<td>0.06</td>
<td>758</td>
<td>768</td>
</tr>
</tbody>
</table>
REFERENCES

(1) National Transportation Research Center, Inc., University Transportation Center, Heavy Truck Rollover Characterization (Phase A) Final Report, 2009

(2) American Transportation Research Institute, Mapping Large Truck Rollovers: Identification and Mitigation Through Spatial Data Analysis, May 2012


(6) Comparative Study of Vehicle Roll Stability, University of Michigan Transportation Research Institute, 1983.

(7) Impact of Specific Geometric Features on Truck Operations and Safety at Interchanges, University of Michigan Transportation Research Institute, 1985

(8) Federal Highway Administration, An Automatic Warning System to Prevent Truck Rollover on Curved Ramps, 1994