TRUCK LOSSES OF
CONTROL PRODUCED BY
PAVEMENT EDGE AND SHOULDER
CONDITIONS

by

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This paper presents an analysis of tractor semi-trailer stability during the traversal of pavement edges. The influence of available friction on the main traveled highway lanes and on the shoulder is included in the analysis.

Published information from 1976 to the present is used along with Michigan's truck simulation program, Phase 4, to study the response of tractor semi-trailers to edge traversal conditions and to illustrate six different responses such a vehicle may exhibit.

These edge conditions are evaluated to compare tractor semi-trailer safety with automobile safety. In so doing, specific conditions are identified where control problems become significant and where loss of control is unavoidable.
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Beginning in 1976 a series of papers reflecting testing (1, 2, 3 & 4), theoretical developments (5 and 6), and computer simulations (6 and 7), have been devoted to the problem of automobile losses of control due to interactions with longitudinal pavement edges. Some of these studies included the influences of different edge heights and shapes, different size automobiles and driver performance. As effective edge heights became greater than 3 inches, the problem of traversal by automobiles became progressively more serious (8). It was clear, as the edge height increased, the potential for a vehicle loss of control also increased. The main problem in traversal of a pavement edge is the "scrubbing" phenomenon. This phenomenon was described for an automobile as follows (8).

1. A vehicle is under control in a traffic lane adjacent to a pavement edge where an unpaved shoulder is lower than the pavement.
2. Through inattention, distraction, or some other reason the vehicle is allowed to move into a position with the right wheels on the unpaved shoulder and just off the paved surface.
3. The driver then carefully tries to steer the vehicle to bring the right wheels back onto the paved surface without reducing speed significantly.
4. The right front wheel encounters the pavement edge at an extremely flat angle and is prevented from moving back onto the pavement. The driver further increases the steer angle to make the vehicle regain the pavement. The vehicle tire continues to scrub the pavement edge, however, and does not respond. At this time there is equilibrium between the cornering forces to the left and the edge force acting to the right.
5. The driver continues to increase the steer input until the critical steer angle is reached and the right front wheel finally mounts the paved surface. Suddenly, in less than one wheel revolution, the pavement edge force has disappeared and the cornering force of the right front wheel may have doubled because of increases in the right front wheel load caused by cornering.

6. The vehicle yaws radically to the left, pivoting about the right rear tire, until that wheel can be dragged up onto the pavement surface. The excessive left turn and yaw continues, and it is too rapid in its development for the driver to prevent penetrating the oncoming traffic lane.

7. A collision with oncoming vehicles or spin out and possible vehicle roll may then occur.

Since large truck tires are some 60 to 100% larger in diameter than automobile tires, it may seem that trucks would find it easier to traverse these edges. This is not necessarily the case. Some characteristics of large trucks might make them more vulnerable to pavement edge problems. These characteristics include 1) different cornering friction development characteristics of truck tires (9), 2) the articulation of tractor semi trailers which makes them vulnerable to jackknife under some conditions (10), 3) relatively low roll stability of many large trucks (11), 4) higher steering ratios, and 5) slower response to steering of these massive vehicles. Some effort was recently made to predict the edge height at which a large truck would roll but this did not relate to a recovery maneuver (12).

In a recent Transportation Research Board publication HVOSM (13) was used to simulate vehicle handling in conjunction with a new theory (6) to predict the edge mounting steer angle. This effort made clear the usefulness of computer simulation in predicting vehicle handling problems associated with pavement edges. Because of the success of that effort the University of Michigan Transportation Research Institute's highly regarded heavy truck simulation, Phase 4 (10), was chosen to see if the same techniques could be applied to the truck/edge interaction problem.

What would one expect to find through such a simulation effort? In the case of automobiles, hazardous conditions were indicated when the vehicle
penetrated the oncoming traffic lane or when the vehicle spun out, perhaps precipitating a roll. As this problem was initially considered, it was predicted that there would be six responses that could develop as a tractor semi-trailer (TST) went off a pavement edge. This would be followed by an attempt on the drivers part to steer the rig back into the appropriate lane. These responses are illustrated by Figures 1 through 6 and are listed in Table 1.

### TABLE 1--Responses of a Tractor Semi-Trailer (TST) Traversing a Pavement Edge

<table>
<thead>
<tr>
<th>Response No.</th>
<th>Response Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The TST is steered back within the appropriate traffic lane.</td>
</tr>
<tr>
<td>2</td>
<td>The TST penetrates the oncoming traffic lane before it can be brought back within the appropriate traffic lane.</td>
</tr>
<tr>
<td>3</td>
<td>The TST rolls after the driver applies countersteering.</td>
</tr>
<tr>
<td>4</td>
<td>The TST rolls due to excessive lateral acceleration as it is steered back across the pavement edge.</td>
</tr>
<tr>
<td>5</td>
<td>The TST jackknifes as it is steered back across the pavement edge.</td>
</tr>
<tr>
<td>6</td>
<td>The TST rolls when the right side wheels drop off the pavement edge.</td>
</tr>
</tbody>
</table>

In the case of the articulated vehicle, it would seem there are control loss possibilities that do not occur in automobiles, and that these vehicles may deserve special consideration when deciding on the safety of pavement edges.

In order to estimate how TST's respond to different edge conditions, it was necessary to determine first how truck tires interact with pavement edges and then to use that information in the Phase 4 Simulation (10). The theory developed to predict the steer angle at which a tire will mount a particular
edge was used to determine this relationship for truck tires (6). That development had shown that the cornering force characteristics of tires as well as their size and shape was of critical importance in determining this relationship. The side force versus slip angle relationship shown in Figure 7 was used to characterize the truck tire. Figure 8 shows the same characteristic for an automobile tire that was used previously (6). The load on these truck and automobile tires was 6000 lbs and 500 lbs respectively.

These side force versus slip angle curves can be reduced to side force coefficient curves simply by dividing the various side forces by the total wheel load. Thus the side force coefficient versus slip angle curves of Figure 9 were produced. Comparing these curves for the automobile tire and the truck tire shows why one might expect the TST to react differently from an automobile in crossing a pavement edge. The initial slope of the truck tire curve is steeper than that of the automobile tire, meaning that it develops more side force, at a lower tire slip angle. This is true up to a slip angle of about seven degrees. At that point, the truck tire has reached its maximum side force capacity while the auto tire continues to increase. It would seem then that were it not for the size effect the auto tire could mount higher edges. It will be shown, however, that the size effect of the truck tire will dominate the edge mounting phenomenon. The next step was to determine the amount of steer angle needed for a truck tire to mount a series of different edge heights. To do this, the theory referred to previously was used with the following input parameters (6).
TRUCK, $W_{Zr} = 6000$ lbs.

AFTER McADAM et al. (10)

AUTOMOBILE, $W_{Zr} = 500$ lbs.

AFTER SAKAI (14)

Figure 7, Side Force Development in a Typical Truck Tire.

Figure 8, Side Force Development in a Typical Automobile Tire.
Figure 9, Comparison of Truck and Automobile Side Force Coefficients.
Figure 10, Steer Angles Required to Mount Edges of Different Effective Heights.
\( r = 21 \) inches (Undeflected radius of the tire)

\( \rho = 5 \) inches (Average tire carcass cross section radius)

\( k = 4500 \text{ lb/in.} \) (Tire stiffness)

\( W_{zr1} = 6000 \text{ lbs} \) (Tire load - front axle)

\( W_{zr1} = 18,000 \text{ lbs} \) (Tire load* - tractor tandem)

\( n = 4.5 \) (Vertical force reduction factor for front axle)

\( n = 12 \) (Vertical force reduction factor for tandem axles)

\( \mu_p = 0.7^{**} \) (Available friction on traffic lane)

\( \mu_e = 0.7^{**} \) (Available friction on edge)

\( \mu_s = 0.56^{**} \) (Available friction on shoulder)

Side Force = \( f(\text{Slip Angle}) \), See Figure 7.

*This is the load on four tires on one side.

**For the truck tire the maximum friction generated is 0.5.

Based on the theory and these parameters, curves B and C of Figure 10 were derived. Curve B is for the tractor front axle tire. Curve C is for each TST tandem axle set. Curve A was previously published for automobiles (6), and was shown for comparison purposes.

Comparing curve B to A is a direct comparison of a truck front tire with an automobile front tire. It is seen, in spite of the overall poorer cornering friction capacity of the truck tire, the size effect, in this case the truck tire being twice as large as the car tire, dominates the relationship and allows the truck tire to mount a pavement edge at a lower value of slip angle. A multi tire effect is what makes the tandem group, shown by Curve C, even less sensitive to the edge height. In that case there are eight tires cornering at the same slip angle to overcome the edge force on a single tire. For this reason, it takes comparatively less slip angle for a tandem group to mount a specific edge. As an example, consider the slip angle required to mount an edge with an effective height of four inches. Figure 10 shows that an
automobile tire would require seven degrees of slip angle compared to a truck front wheel tire requiring only three degrees, and a tire on a tandem set of eight tires requiring about one degree. Therefore in the zone where the scrubbing phenomenon takes place for an automobile, the truck tire would mount more easily at a lower slip angle. In the range of five to six inch edge height, however, the scrubbing phenomenon quickly becomes quite critical for trucks, especially if the driver chooses to input large values of wheel steering angle. A ten degree wheel steering angle might correspond to some 280 degrees of steering wheel rotation by the driver. Since no additional cornering force is developed in the typical truck tire for steering angles above six degrees, it might even seem that steering angles above six degrees would not present a more hazardous condition. This is not true since the amount of steering angle relates to how fast the diver can get the angle removed once the truck mounts the pavement.

The roughness of a shoulder below an edge drop on a typical highway also has an influence. Consider a driver who allows the right side of his rig to go over a ten inch edge. The driver then cranks in 360° of steering wheel movement (15° of wheel angle) in attempting to remount the edge, Figure 10 would predict that the edge could not be mounted. If, however, an elevated section where the edge height decreased to six inches or lower, or a bump was struck that caused the front wheel to rise several inches, the edge then might be mounted, and sharp cornering to the left would occur. Then it might take a rotation of perhaps 15° by the tractor before the tractor tandems could mount. The result might well be a jackknife or TST roll due to excessive cornering. Obviously it would take much longer for the driver to unwind the initial 360° of steering wheel rotation and then steer back to the right than would be the case if he had input only 168°, the amount necessary to cause maximum cornering force.
Although it is probably possible to intuitively derive the various problems that a TST might encounter under certain edge conditions based primarily on Figure 10, there is a simulation that may be used to avoid much of the conjecture thus evolved. That simulation is Michigan's Phase 4 (10). Many different configurations could be studied in this way. For the illustrative purposes of this paper only two configurations are used. The first, TST1, represents a comparatively common COE Tractor/Van Trailer loaded in a way somewhat in between Cases A and B of Figure 11 (11). The second vehicle, TST2, is similar to TST1 in all respects except the load cg height, which was reduced from 87 in. to 60 in.

The major descriptive elements of TST1 and TST2 are given in Table 2. A complete listing of input parameters for use in Phase 4 is available from the writers.

<table>
<thead>
<tr>
<th>TABLE 2--Tractor Semi-Trailers Used in Simulation Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractor Characteristics</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Wheelbase</td>
</tr>
<tr>
<td>Front Track Width</td>
</tr>
<tr>
<td>Tandem Track Width</td>
</tr>
<tr>
<td>Trailer Characteristics</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Load</td>
</tr>
<tr>
<td>Tandem Track Width</td>
</tr>
<tr>
<td>Wheelbase</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Load cg height above ground</td>
</tr>
<tr>
<td>Run Designation</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>TST1-1</td>
</tr>
<tr>
<td>TST1-2</td>
</tr>
<tr>
<td>TST1-3</td>
</tr>
<tr>
<td>TST1-4</td>
</tr>
<tr>
<td>TST1-5</td>
</tr>
<tr>
<td>TST2-1</td>
</tr>
<tr>
<td>TST2-2</td>
</tr>
<tr>
<td>TST2-3</td>
</tr>
</tbody>
</table>

TABLE 3--Results of Simulated Maneuvers at 50 mph.
The various simulations were conducted in the following way. A combination of effective edge height and initial steer angle was chosen from Figure 10. For example, if the mounting of an edge height of four inches was to be simulated, Figure 10, Curve B, would indicate that a steering angle of three degrees would be needed to mount the edge. The TST simulation was then placed moving straight ahead at a speed of 50 mph with an initial steer angle of three degrees.

Based on research described previously (6), a perception reaction time of 0.5 seconds was chosen with a rate of countersteering of 12 degrees per second. That is, 0.5 seconds after the edge was mounted, the driver began to countersteer in an effort to keep his vehicle in the adjacent traffic lane. The rate at which he countersteers is consistent with a steer angle change of 12 degrees per second, which in turn is consistent with 16 degrees per second in automobiles (6), if the difference in the steering ratios of trucks and autos is considered.

With these initial and countersteering characteristics, the simulation then gives a comprehensive estimate of the vehicle trajectory, whether it penetrates an oncoming traffic lane, whether roll or jackknifing takes place, and if so when these responses take place.

When this work was first planned, it was considered important to constrain first the tractor tandems and then the trailer tandems to a trajectory coincident with the pavement edge until the yaw angle necessary to mount the edge was reached. The way this was done was by an iterative procedure. First the steering axle tire mounting angle was selected and the simulations were run without constraining either tractor or trailer tandems to the edge trajectory. Then the results were examined to determine when the tractor reached the critical yaw, as dictated by Figure 10 when the tandems would mount the edge. The cornering forces on the tractor tandems from time zero to the critical yaw time were used to estimate the edge force necessary to resist tandem lateral
movement. That gradually increasing edge force was put in the simulation as an external force acting over the time period at a point on the front right tandem wheel in a direction perpendicular to the tractor longitudinal axis. The simulation was then run again, this time determining the time necessary, after tractor tandem mounting, for the yaw angle of the trailer to reach the critical mounting angle for the trailer tandems. Again, from the cornering forces on the trailer tandems the edge force was estimated to keep the trailer tandems adhering to the trajectory of the pavement edge until the appropriate time.

Finally, the simulation was run with edge forces varying with time on both tractor and trailer tandems which constrained them appropriately until they could be expected to mount the edge.

For the high cg and high edge conditions a further imposed moment was used to simulate the cg movement due to the right side of the TST dropping off the edge to the lower surface of the shoulder. The cg lateral movement was calculated due to the body roll of the trailer and a moment was imposed which simulated that movement. This was necessary because the simulation was actually run on level terrain.

Table 3 gives the basic results of eight selected simulation runs. In interpreting this table the following definitions are needed.

TST1 - a basic COE/Van Trailer unit with a high load cg height (See Table 2 for a more detailed description).

TST2 - a basic COE/Van Trailer with a low load cg height (See Table 2 for a more detailed description).

Response 1 - the adjacent traffic lane is safety regained.
Response 2 - the opposing traffic lane is violated.
Response 3 - the TST rolls after the countersteering takes effect.
Response 4 - the TST rolls when the initial edge mounting occurs.
Response 5 - the TST jackknifes as the edge mounting is attempted.
Response 6 - the TST rolls on shoulder when the right wheels drop off the edge.
<table>
<thead>
<tr>
<th>CASE</th>
<th>CONFIGURATION</th>
<th>WEIGHT (lbs.)</th>
<th>PAYLOAD CG HEIGHT (in.)</th>
<th>ROLLOVER THRESHOLD (G's)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Full Gross, Medium-Density Freight (34 lb/ft³)</td>
<td>80,000</td>
<td>83.5</td>
<td>.34</td>
</tr>
<tr>
<td>B</td>
<td>'Typical' LTL Freight Load</td>
<td>73,000</td>
<td>95.0</td>
<td>.28</td>
</tr>
<tr>
<td>C</td>
<td>Full Gross, Full Cube, Homogeneous Freight (18.7 lb/ft³)</td>
<td>80,000</td>
<td>105.0</td>
<td>.24</td>
</tr>
<tr>
<td>D</td>
<td>Full Gross Gasoline Tanker</td>
<td>80,000</td>
<td>88.6</td>
<td>.32</td>
</tr>
<tr>
<td>E</td>
<td>Cryogenic Tanker (He₂ and H₂)</td>
<td>80,000</td>
<td>100.0</td>
<td>.26</td>
</tr>
</tbody>
</table>

Figure 11, Loading Data and Resulting Rollover Thresholds for Example Tractor-semitrailers at Full Load. (After Ervin, MacAdam and Barnes [11])
It will be seen that the conditions were selected so that each of the unsafe responses is illustrated.

TSTI-1 mounting a four inch edge violated the oncoming traffic lane about two feet and was very close to rolling after countersteering was applied. It gives a good roll boundary for this type TST.

TSTI-2, -3, and -4, as edge height increases to 5.5, 5.8, and 6.0 in, progressively emphasize response 2 and response 3, finally giving a boundary point for response 4.

TSTI-5 simply illustrates how a TST will roll when the wheels drop off the edge, if the edge is high enough. This is response 6.

Now considering the low cg TST, TST2-1, shows how the oncoming traffic lane may be violated with only a four inch edge condition. TST2-2 shows an extreme example of the traffic lane violation, response 2, when a six inch edge is encountered.

Finally, TST2-3 illustrates how a TST can "hang up" on a large ten inch edge, resulting in a very high tractor yaw angle (about 15 degrees) before the tractor tandems can mount, and finally a jackknife (response 5).

By interpreting three items the figure summarizing all available information on TST handling and stability relative to crossing pavement edges maybe developed. These three items are Figure 10, Figure 12 and Table 3. The summary of this information is given by Figure 13. Figure 10 shows the required steer angle for various truck tires to mount various effective edge heights. Figure 12, developed during the work on construction zones (12) shows the effective edge heights for different shape edges and Table 3 gives the results of TST simulations for a low and high cg TST mounting, or attempting to mount, six different edges. Figure 13, is an effort to generalize the problem of edges for TST's. Like the chart that was originally devised for automobiles (4), it is divided into five zones of safety. Those zones are defined as follows:
Figure 12. Effective Edge Height Based on Edge Shape and Total Edge Height
Figure 13, Safety Chart for TST's Mounting Pavement Edges.
Safe - The pavement edge should have nothing to do with any TST loss of control.

Reasonably Safe - A prudent driver of a reasonably maintained TST would experience no significant problem in traversing the pavement edge.

Marginally Safe - Many drivers in all but very high load cg TST’s could safely traverse this pavement edge. Some drivers would experience difficulty in performing the scrubbing maneuver and remaining within the adjacent lane. TST’s with cg load heights of 80 inches or above might roll as the effective edge height approaches four inches.

Questionable Safety - Most drivers would be unable to safely perform the scrubbing/edge mounting maneuver. Violation of the oncoming traffic lane and/or rolling and/or jackknifing, are likely events.

Unsafe - Loss of control highly probable. Violation of oncoming traffic lane, and/or rolling and/or jackknifing will occur.

A brief description of the considerations necessary to produce Figure 13 will be given. If one can decide how the curve for Shape A, the sharp 90 degree edge, is to lie relative to the five zones of safety, it might then be possible to derive the curves for Shapes B and C from Shape A. With that understanding, the placement of the Shape A curve will be described. Referring to Table 3, it will be seen that TST1-1 shows a significant problem developing with respect to penetration of the oncoming traffic lane and to TST roll during countersteering when the edge height is four inches. Therefore, a point on the curve is placed on the line between "Marginally Safe" and "Questionable Safety" directly above four inches. This would be the start of response 3. Consideration of the simulation output led to the conclusion that response 2, just slightly penetrating the oncoming traffic lane would not start until the edge height
exceeded three inches, therefore a point was placed on the line between "Reasonably Safe" and "Marginally Safe" directly above three inches. Considering TST1-2 through -4 shows responses 2 and 3 becoming more pronounced as the edge height increases above four inches, finally achieving response 4 as the height reaches six inches. Therefore the curve penetrates increasingly less safe zones as a six inch edge height is approached. In the zone of six to eight inches, an extremely unsafe condition would govern producing the critical roll and jackknifing responses 4 and 5.

At eight inches, a major discontinuity in the Shape A curve was produced, lowering the curve into the "Marginally Safe" zone. This is because it becomes theoretically impossible to mount a sharp edge of eight inch height from the scrubbing condition. This is seen in Curve B of Figure 10, where an infinite steer angle would be required to mount as the edge height becomes greater than six inches. This discontinuity was placed at eight inches rather than at six inches in an effort to be conservative and in recognizing that there are no perfectly smooth shoulders. If there is a significant bump along a nominally eight to ten inch edge, mounting could occur along edges in the eight to ten inch zone.

As the edge height then increases, approaching twelve inches, it becomes increasingly less safe since response 6 is approached by relatively high cg vehicles, i.e. the TST simply rolls to the right when the wheels drop off the pavement edge.

Finally the curves for Shape B (rounded edge) and Shape C (45° inclined edge) were derived from the placement of the Shape A curve and Figure 12. Figure 12 is based on the effective edge height concept published previously (6).

The result of these considerations is the understanding that TST's are not significantly less sensitive to pavement edges in spite of the size effect that had originally been considered of overriding importance. The other important
factors that compensate for the size effect are the different cornering friction properties of truck tires, the slower rate at which a driver can produce countersteering due to higher steering ratios and the slower response of these massive vehicles to cornering forces. When the curves of edge Shapes A, B and C in the range of zero to six inches of elevation change, are compared for automobiles (8) and trucks (Figure 13) it is seen there is very little difference. The major differences arise in the higher edge drop situation when the lower roll stability of TST's becomes very important.

Finally, it is concluded that the guidelines recommended for edge and shoulder maintenance in 1983 (4) and the recent guidelines for treatment of edges in construction zones (12) are as appropriate for TST's as they are for the vehicle which was then given primary consideration, the automobile.

DEDICATION

To Edythe Mae Hart Ivey, matriarch of the Texas Hart-Ivey family. She has taught three generations how to live. She is now beginning to teach the fourth.
REFERENCES


