EFFECTS OF CROSS-SLOPE BREAK ON ROADWAY DEPARTURE RECOVERY FOR TRUCKS ON HORIZONTAL CURVES

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For TRB 2015 Annual Meeting
Submission date: July 29, 2015
Resubmitted: November 13, 2015

TOTAL WORDS: **7479** [4229 Words, 7 Figures (1750), 6 Tables (1500)]
Abstract: 188 words, Text: 3705 Words, References: 336 Words

ABSTRACT

A 2009 crash involving a tanker truck that departed the roadway on a freeway connection ramp led the National Transportation Safety Board to suggest a review of current AASHTO policy for pavement/shoulder cross-slope breaks on horizontal curves to determine whether updates to the design criteria are needed. As part of NCHRP Project 3-105, the research team reviewed and summarized existing policies and conducted a pair of studies focusing on large trucks on horizontal curves. Researchers conducted a vehicle dynamics simulation study and a crash-based study; both were designed to identify patterns and trends in roadway departure crashes involving large trucks and develop recommendations for corresponding revisions to AASHTO policy for designing cross-slope breaks on horizontal curves. In the vehicle dynamics simulation study, researchers developed and analyzed results from roadway departure models for a tractor/single-van-trailer truck, a tractor/tanker-trailer truck, and a tractor/double-van-trailer truck for various combinations of roadway departure path, approach speed, superelevation, and cross-slope break. This paper summarizes existing policy, describes the study methodology, and presents findings from the vehicle dynamics simulation study. Results indicate that no changes need to be recommended to AASHTO's policy on cross-slope break.

BACKGROUND

In 2009 a tanker truck overturned and caught fire while negotiating an interchange ramp near Indianapolis, Indiana. The National Transportation Safety Board (NTSB) conducted a detailed investigation of the crash (*1*). From the investigation, the NTSB concluded that the transition from positive to negative cross-slope as the tanker truck moved from the right lane onto the shoulder significantly decreased the speed at which the truck could negotiate the curve without rolling over. NTSB stated that guidance on pavement/shoulder cross-slope break in the 2004 edition of the American Association of State Highway and Transportation Officials (AASHTO) publication *A Policy on Geometric Design of Highways and Streets* (commonly known as the *Green Book*) did not account for low-stability heavy trucks susceptible to rollover. The NTSB made several recommendations for consideration by the Federal Highway Administration (FHWA) and AASHTO, including a review of current AASHTO policy for pavement/shoulder cross-slope breaks on horizontal curves to determine if updates to the design criteria are needed.

AASHTO's current policy states that shoulder slopes that drain away from the paved surface on the outside of a superelevated horizontal curve should be designed to avoid too great a cross-slope break, calculated as the algebraic difference between the cross-slope of the traveled way and shoulder (*2*). To avoid large pavement/shoulder cross-slope breaks, it may be desirable that all or part of the shoulder be sloped upward at about the same or lesser rate than the superelevated traveled way. Where this is undesirable due to potentially adverse conditions, the cross-slope break should be limited to approximately 8 percent by flattening the shoulder on the outside of the curve. Alternatives to a severe cross-slope break include a continuously rounded shoulder on the outside of the superelevated traveled way or a planar shoulder with multiple breaks in the cross-slope. The *Roadside Design Guide* (*3*) prefers a rounded roadside, because it reduces the chances of an errant vehicle becoming airborne and affords the driver more control over the vehicle. FIGURE 1 shows a typical cross-section for a superelevated curve.

Little change has occurred in AASHTO policy on cross-slope break over the years. In the 1957 *A Policy on Arterial Highways in Urban Areas* and the 1965 *A Policy on Geometric Design of Rural Highways*, AASHO recommended a maximum cross-slope break of 7 percent (*1*). Since at least the 1990 *Green Book*, AASHTO's recommended maximum cross-slope break has been 8 percent. The 2011 *Green Book* also states that the algebraic difference in cross-slopes at the edge of the traveled way should not exceed 8 percent, to avoid an undesirable rollover effect.

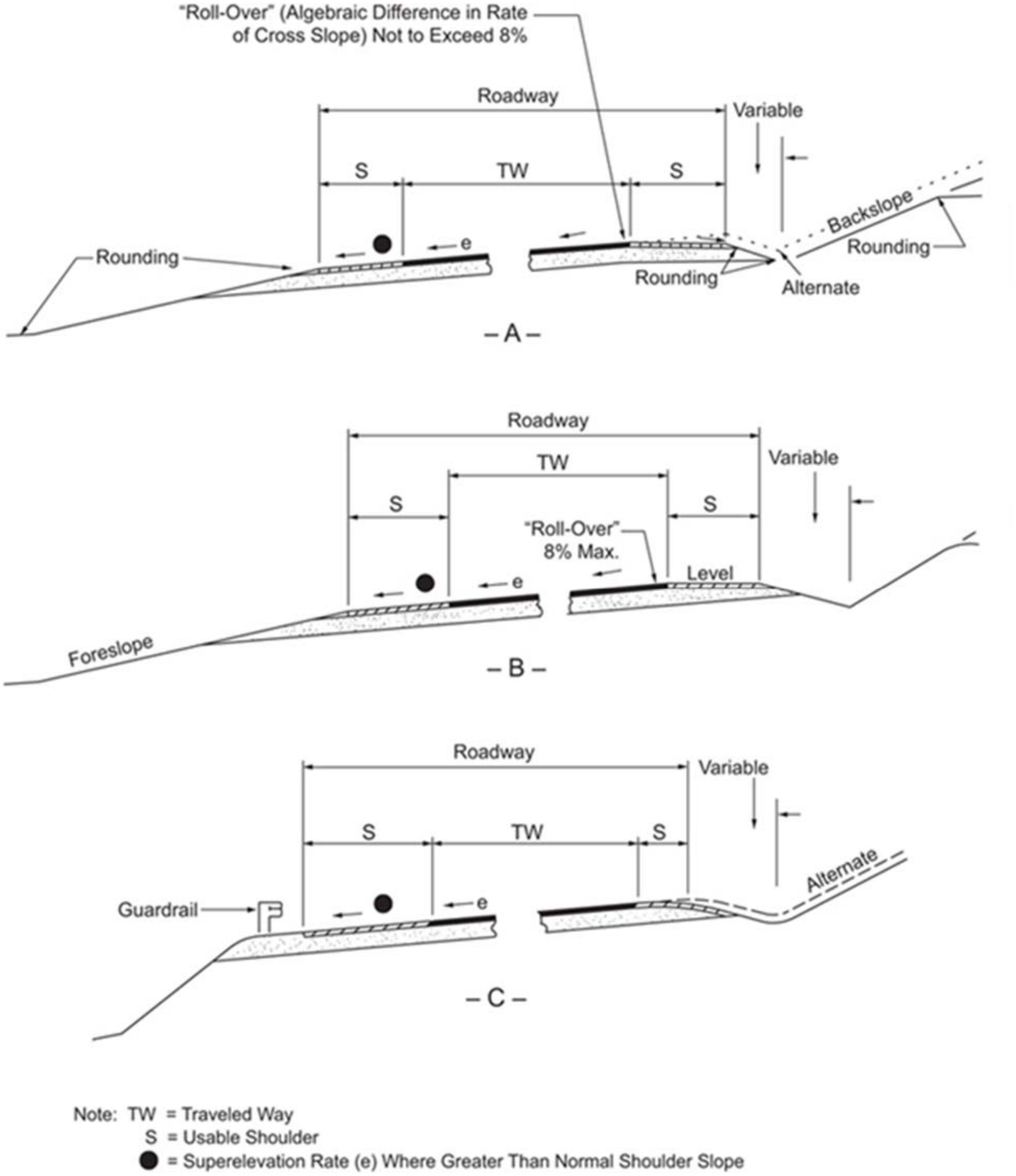


FIGURE 1 Typical superelevated cross-section (*2*).

The current 8 percent maximum cross-slope break criterion appears to be based on a 1981 FHWA study (*4*), which used the Highway-Vehicle-Object Simulation Model (HVOSM) to evaluate cross-slope break designs by testing the effects of curvature, speed, and path of a simulated 1971 passenger car; trucks were not considered in the research. Given changes in vehicle design and composition of traffic since the 1970s, there was a need for a detailed investigation of cross-slope break design criteria to determine if the existing policy is appropriate for the current fleet of passenger cars and trucks.

As part of NCHRP Project 3-105, the research team assessed the current AASHTO design policy for pavement/shoulder cross-slope breaks on the outside of horizontal curves to determine whether updates in design criteria are needed. Although a highly publicized crash on an interchange ramp was the impetus for the research, the project scope was not limited to curves on ramps but rather investigated pavement/shoulder cross-slope break conditions for the design of horizontal curves in general. Two separate work plans, one involving vehicle dynamics simulation modeling and a second involving a crash-based safety analysis, were executed to fulfill the objectives of this research. The objective of the crash-based safety analysis was to investigate the effect of pavement/shoulder cross-slope break on crash frequency and severity. The results of the detailed crash-based safety analysis do not definitively answer the question of whether the magnitude of the pavement/shoulder cross-slope break affects crash frequency and severity, in part because the available sample size was simply too small to draw meaningful conclusions. Therefore, recommendations regarding changes to AASHTO's current policy for pavement/shoulder cross-slope break were based on the results of vehicle dynamics simulation modeling. This paper discusses the activities and findings from the vehicle dynamics portion of the research.

PREVIOUS RESEARCH

Cross-Slope Break Research

Glennon led two studies (*4*,*5*) in the 1980s that investigated cross-slope break design and related issues. In 1981, Glennon et al. (*4*) studied cross-slope break issues on highway curves, using the McHenry version of HVOSM. Glennon et al. compared cross-slope break to design curvature, vehicle path, superelevation, and speed. The study used only a passenger car, a 1971 Dodge Coronet, as the design vehicle and did not include trucks due to HVOSM limitations.

Glennon et al. considered a circular design path and varied the radius of curvature. Of the many types of lane departures possible, they considered only a moderate departure, in which the vehicle was steered back to the driving lane, assuming the shoulder width was not a limiting factor. The path of vehicle departure chosen is represented in Equation (1).

$$R_v = \frac{19{,}825 * R}{R + 23{,}096} \quad (1)$$

where R = radius of the horizontal curve (ft)
R_v = radius of the vehicle path (ft)

This equation represents the 95th percentile transient path and was established based on highway operational studies conducted by Glennon and Weaver (*6*).

Comparing the performance criteria for lateral friction demand and driver discomfort, they concluded that driver discomfort was the limiting criterion. Based on a Calspan study (*7*) and the safety-conservative design philosophy modeled by AASHTO, they rationalized that a maximum discomfort level of 0.3 g was appropriate, and they recommended a single maximum cross-slope break of 8 percent for wide shoulders. Glennon et al. also determined that recovery from an all-wheel traversal (i.e., 4-wheel departure) was more informative because it produced more extreme responses to cross-slope break than a partial departure (i.e., 2-wheel departure).

In the 1983 study, Glennon et al. (*5*) looked at the effects of cross-slope and centerline cross-slope break on lateral tire acceleration, vehicle roll angle, and driver comfort using

HVOSM and the Highway Safety Research Institute/Motor Vehicle Manufacturers Association Phase 4 (HSRI/MVMA) simulation model. The study highlighted the need to provide a cross-slope design consistent with drainage requirements.

Driver Behavior Studies

A 1977 study conducted by the Society of Automotive Engineers (SAE) observed a sedan at 37 mph faced with an emergency that is 1.3 seconds to collision (*8*). The severity of the scenario forced the driver to perform an emergency avoidance maneuver without braking. In the test, drivers were told to avoid collision by simulating a lane change through a lateral displacement of 12 ft. The most common maximum resultant steering angle was between 210 and 230 degrees, but the study did not provide guidance for the behavior of a driver returning to the lane of travel.

Kim et al. conducted a similar study using a driving simulator, recording driver response to an emergency that is 1.3 seconds to collision with no braking (*9*). The simulator tested a sedan at 31 mph driving behind a truck that stopped suddenly on a straight road with a friction coefficient of 0.8. The scenario included data for the vehicle to return to the travel lane. The subjects' avoidance steering was typically between +40 and +80 degrees, while recovery steering was commonly -80 degrees, resulting in a maximum steering angle generally between 120 and 180 degrees.

Critical Design Elements and Variables

In NCHRP Report 505, Harwood et al. (*10*) summarized research results that assessed whether geometric design criteria for highways and streets can reasonably accommodate the characteristics of the current and future truck fleet on the U.S. highway system. Relevant findings from the research include:

- The current *Green Book* criteria for cross-slope breaks and vertical clearances appear to be appropriate for the current truck fleet.
- The minimum rollover threshold for trucks is generally between 0.35 and 0.40 g. This threshold generally applies to trucks fully loaded with uniform-density cargo.
- When a high-speed vehicle moves through a curve, the rear axles of the vehicle tend to move outward (e.g., high-speed offtracking), acting in opposite direction to low-speed offtracking. At lower speeds, low-speed offtracking predominates; as speed increases, the net offtracking is reduced such that at sufficiently high speeds, the two phenomena cancel out, resulting in no net offtracking. High-speed offtracking is usually not a significant factor in roadway design, compared with low-speed offtracking.

During research to develop superelevation criteria for sharp horizontal curves on steep grades, Torbic et al. (*11*) conducted field studies and vehicle dynamics simulations to investigate combinations of horizontal curve and vertical grade design criteria. Vehicle types considered in the research included passenger cars and trucks. Relevant findings from this research include:

- For passenger cars, mean maximum wet-tire friction values ranged from approximately 0.91 to 0.82, and mean skidding wet-tire friction values ranged from approximately 0.67 to 0.58 in the longitudinal (braking) direction. For trucks, the corresponding friction value ranges were approximately 0.82 to 0.78 and 0.59 to 0.54, respectively.
- The margins of safety against skidding were slightly higher for the tractor/double-van-trailer truck when compared to the tractor/single-van-trailer truck.

- Assuming the center-of-gravity (CG) height and track width of the trailers for both vehicles are the same, tractor/double-van-trailer trucks have very similar rollover margins of safety as compared to tractor/single-van-trailer trucks.

VEHICLE DYNAMICS SIMULATION MODELING

As part of NCHRP Project 3-105, the research team developed a methodology for vehicle dynamics simulation modeling to determine the effect of cross-slope break on a vehicle's ability to recover from encroachment over the cross-slope break when navigating a curved roadway. FIGURE 2 illustrates the general simulation process. Combinations of key geometric design elements and other critical elements were simulated in TruckSim (*12*) to assess their impact on vehicle stability when encountering a range of cross-slope breaks between the traveled way and shoulder, including:

- Vehicle type
- Vehicle speed
- Vehicle trajectory
- Cross-slope break rate
- Superelevation rate
- Extent of vehicle encroachment

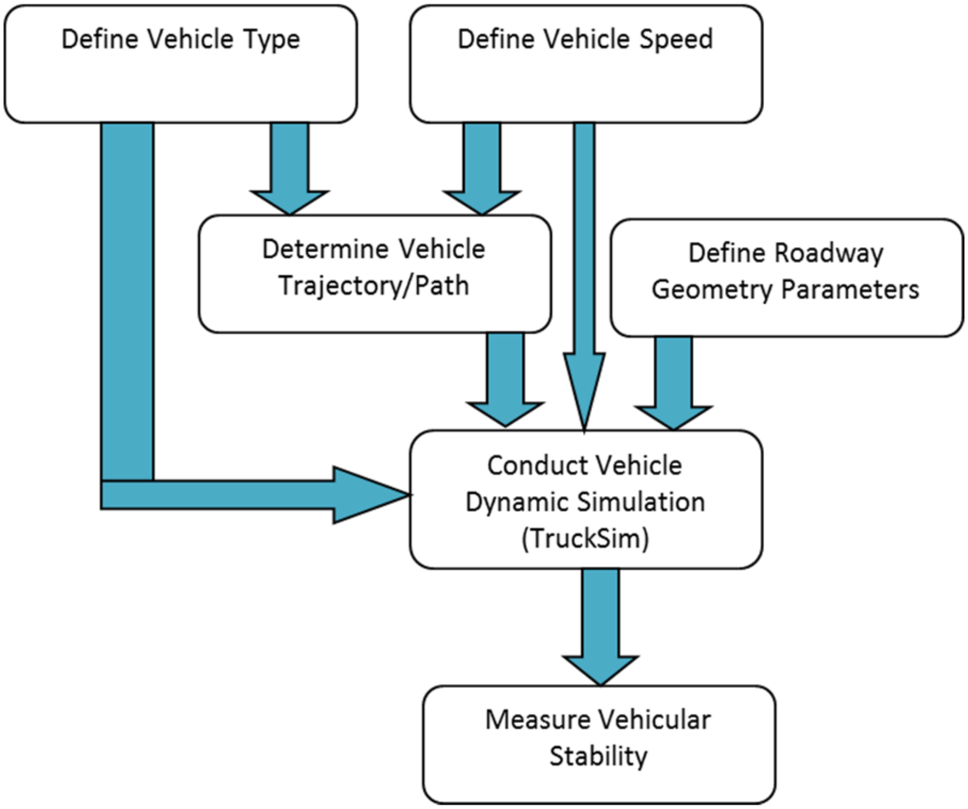


FIGURE 2 Simulation process.

Select Design Speed and Roadway Geometry for Simulation

The roadway is defined by a combination of speeds, superelevation rates, and cross-slope break rates. TABLE 1 summarizes the minimum design radii for design speeds and superelevation rates selected for simulation. All simulation scenarios were based upon minimum-radius curves as defined in the *AASHTO Green Book* (*2*) and vehicles traveling at the design speed of the curve. A 12-ft travel lane was assumed for all simulations, along with a continuous-width paved shoulder.

TABLE 1 Specified Minimum Design Radius

	Minimum Radius (ft) for a Superelevation of…		
Design Speed	4%	6%	8%
30 mph	250	231	214
50 mph	926	833	758
60 mph	1500	1330	1200
70 mph	N/A[a]	2040	1810

[a] N/A = not applicable. A 70-mph design speed with a 4 percent superelevation is not an applicable design scenario in the *AASHTO Green Book*.

A variety of pavement/shoulder cross-slope breaks were investigated for each design curve. Five cross-slope break rates were considered in the assessment: 0, 4, 6, 8, and 10 percent. For the simulations, a dry surface coefficient of friction of 0.8 for tire rolling resistance was assumed, based on recent studies (*9, 11*).

Vehicle Types and Models

Three vehicles were simulated in the research: a tractor/single-van-trailer truck, a tractor/tanker-trailer truck, and a tractor/double-van-trailer truck. Input parameters for the vehicles were selected based on vehicle dimensions from the *AASHTO Green Book* (*2*), and mass and center of gravity values were obtained from the AASHTO *Manual for Assessing Safety Hardware (MASH) (13)*. Default TruckSim models were modified with the dimensions and weights for each of the vehicle types. TABLE 2 shows the primary vehicle input parameters used in TruckSim.

TABLE 2 Primary Vehicle Input Parameters Used in TruckSim

Vehicle Inputs	Tractor/single-van-trailer truck	Tractor/tanker-trailer truck (full tanker)	Tractor/double-van-trailer truck
Design vehicle	WB-62	WB-62	WB-67D
Tractor type	Sleeper Cab	Sleeper Cab	Day Cab
Total weight of vehicle[a] (lb)	80,158	80,161	80,151
Total weight of tractor (lb)	18,629	18,629	12,698
Total weight of trailer(s) (lb)	15,999	15,999	17,262 (two trailers + dolly)
Trailer ballast (laden) (lb)	45,358	45,358	48,610 (both)
Height of center of gravity of trailer ballast (in)	73	81	73
Offset of center of gravity from middle of trailer (in)	0	0	0
Total length of vehicle (ft)	69	69	72
Total length of trailer to back axle (ft)	44.2	44.2	24.1
Distance from front axle to center of tandem of tractor (ft)	18.5	18.5	11.5

[a] Weight of vehicle model verified by summing the tire forces underneath the vehicle driving along a flat road.

One loading configuration was simulated for each truck type. Existing vehicle dynamics simulation models do not have the capability to simulate the dynamic effects of liquid sloshing in a tanker trailer; therefore, the tractor/tanker-trailer truck was simulated by modifying the center of gravity of the tractor/single-van-trailer truck. Only the fully-loaded trailer condition was selected for evaluation of pavement/shoulder cross-slope breaks as it was assumed that the dynamic effects of liquid sloshing should be minimal for the fully-loaded trailer condition.

Vehicle Departure Models

Two vehicle trajectories were selected for evaluation of pavement/shoulder cross-slope breaks:

- Partial traversal moderate departure: The vehicle gradually drifts from the middle of the travel lane along a path tangent to the roadway curvature and only the passenger-side tires of the vehicle traverse the cross-slope break and encroach onto the shoulder before the vehicle is steered back to the travel lane. This vehicle trajectory represented the mildest departure scenario simulated as part of this research.
- Full traversal moderate departure: The vehicle gradually drifts from the middle of the travel lane along a path tangent to the roadway curvature and all tires of the vehicle traverse the cross-slope break and encroach onto the shoulder before the vehicle is steered back to the travel lane. The full traversal trajectory was more severe than the partial traversal trajectory in accordance with Glennon et al. (*4*). This vehicle trajectory served as the basis for AASHTO's current design policy on pavement/shoulder cross-slope break.

A third vehicle trajectory was used for testing the vehicle dynamics simulation model to verify that realistic results were being obtained and to assess the primary combinations of simulation scenarios to be tested in this research:

- Full traversal severe departure: The steering inputs represent the situation where the driver steers to avoid an obstacle in the travel lane (i.e., a collision avoidance maneuver) while traversing a horizontal curve and all tires of the vehicle traverse the cross-slope break and encroach onto the shoulder before the vehicle is steered back to the travel lane. This vehicle trajectory represents an emergency collision-avoidance maneuver so extreme that rollover is likely in some cases even if no cross-slope break is present. This vehicle trajectory represented the most extreme maneuver simulated as part of this research. The results from the full traversal severe departure simulations were not directly considered when making decisions regarding design criteria for cross-slope breaks as this maneuver was considered too extreme to serve as a basis for determining design policy.

The severe departure maneuver was tested only with a full traversal departure scenario. The defined steering path for this collision avoidance maneuver was based upon data gathered by Kim et al. (*9*) FIGURE 3 presents the generated trajectories for a vehicle traveling at 50, 60, and 70 mph. The generated path for a vehicle speed of 50 mph was checked against the original longitudinal vs. lateral position graph developed by Kim et al. to validate the path function, and the two graphs proved to be compatible and showed favorable resemblance.

Although these generated paths represent the collision avoidance maneuver executed by the driver at different speeds, they do not constitute a full lane departure. The maximum lateral displacement from the centerline of the travel lane was 9.18 ft, which is not adequate for all tires of the vehicle to interact with the pavement/shoulder cross-slope break. To allow the vehicle to fully cross onto the shoulder, the paths were uniformly scaled to accommodate a total lateral displacement of 10.40 ft from the centerline of the travel lane and a displacement of the centerline of the vehicle of 4.40 ft.

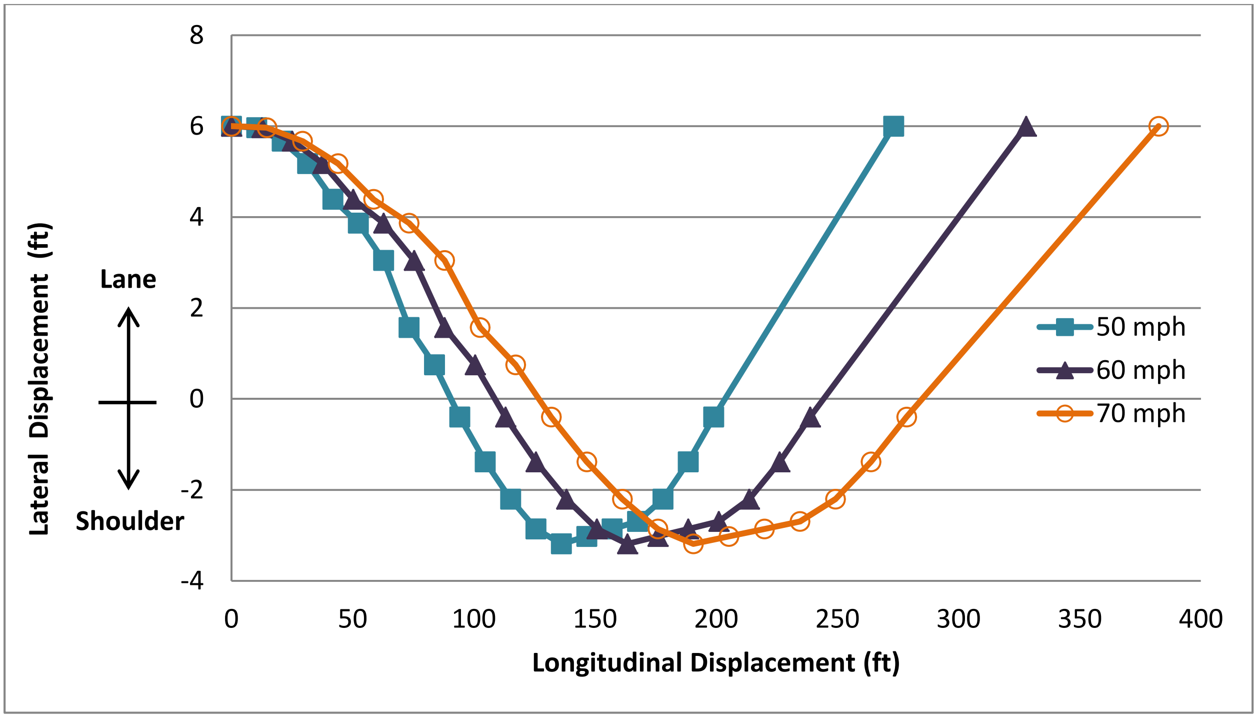


FIGURE 3 Vehicle paths generated by path function for collision avoidance maneuver (severe departure).

FIGURE 4 illustrates the defined path for a moderate vehicle departure. The lateral displacement (i.e., delta) is considered constant with respect to the partial and full departure parameters established relative to the width of the vehicle. The trajectories illustrated in FIGURE 4 represent the lateral displacement of the centerline of the vehicle from the pavement/shoulder cross-slope break boundary for a sample scenario. This method was used to define the geometries of the vehicle paths for use in TruckSim.

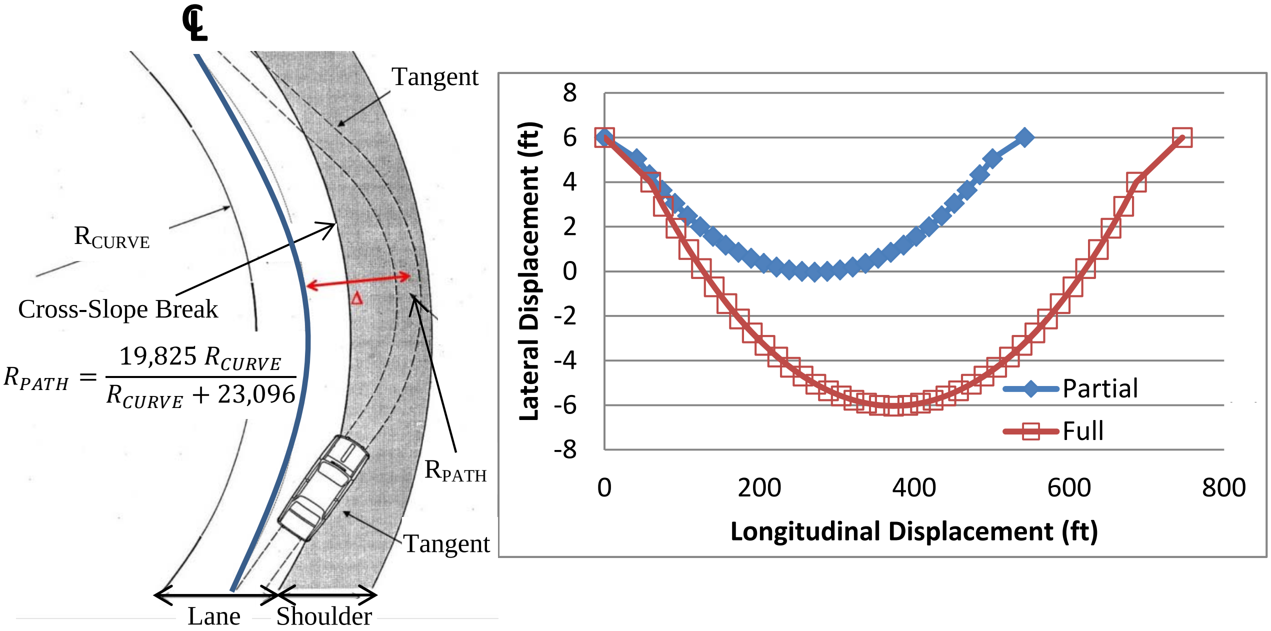


FIGURE 4 Conceptual moderate vehicle departure model and vehicle trajectory/path.

The partial and full traversal moderate departure vehicle trajectories represent realistic situations on which design of pavement/shoulder cross-slope breaks should be based. The appropriate design criterion is that a cross-slope break should not induce rollover by a truck in a situation in which rollovers do not occur in the absence of a cross-slope break. Researchers simulated many combinations of vehicle type, speed, encroachment, and geometry of partial traversal and full traversal moderate departure vehicle trajectories.

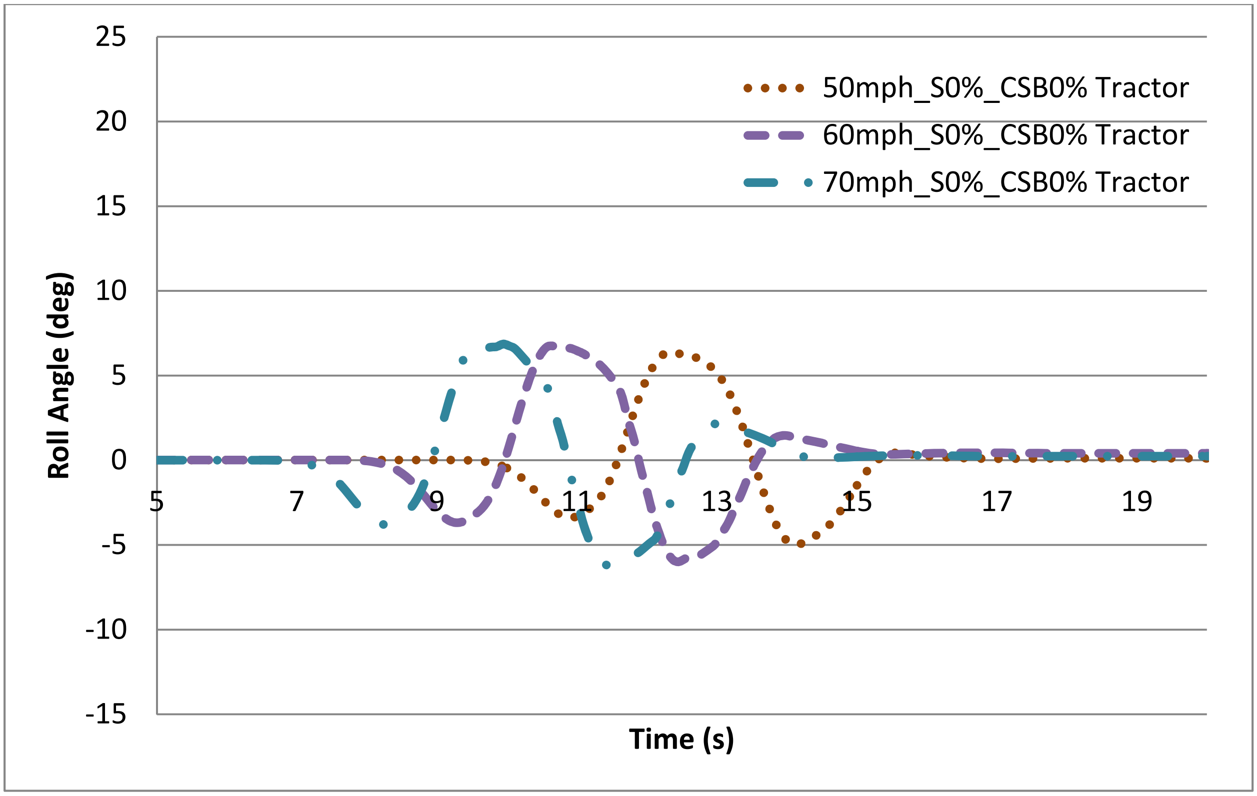
Preliminary Simulations

Preliminary simulations of a tractor/single-van-trailer truck encroaching onto the right shoulder and encountering various cross-slope breaks were conducted to identify the primary scenarios to be simulated in this research. First a tractor/single-van-trailer truck traversing a tangent section of roadway with zero superelevation and zero cross-slope break was simulated. Because the superelevation of this tangent section of roadway was zero, the initial roll angle of the vehicle was also zero. The initial roll angle increases as superelevation increases, but the roll angle does not equal the superelevation because the vehicle suspension compensates partially for the slope in the road surface. A positive roll angle is a roll toward the passenger side of the vehicle, and a negative roll angle is a roll toward the driver side of the vehicle.

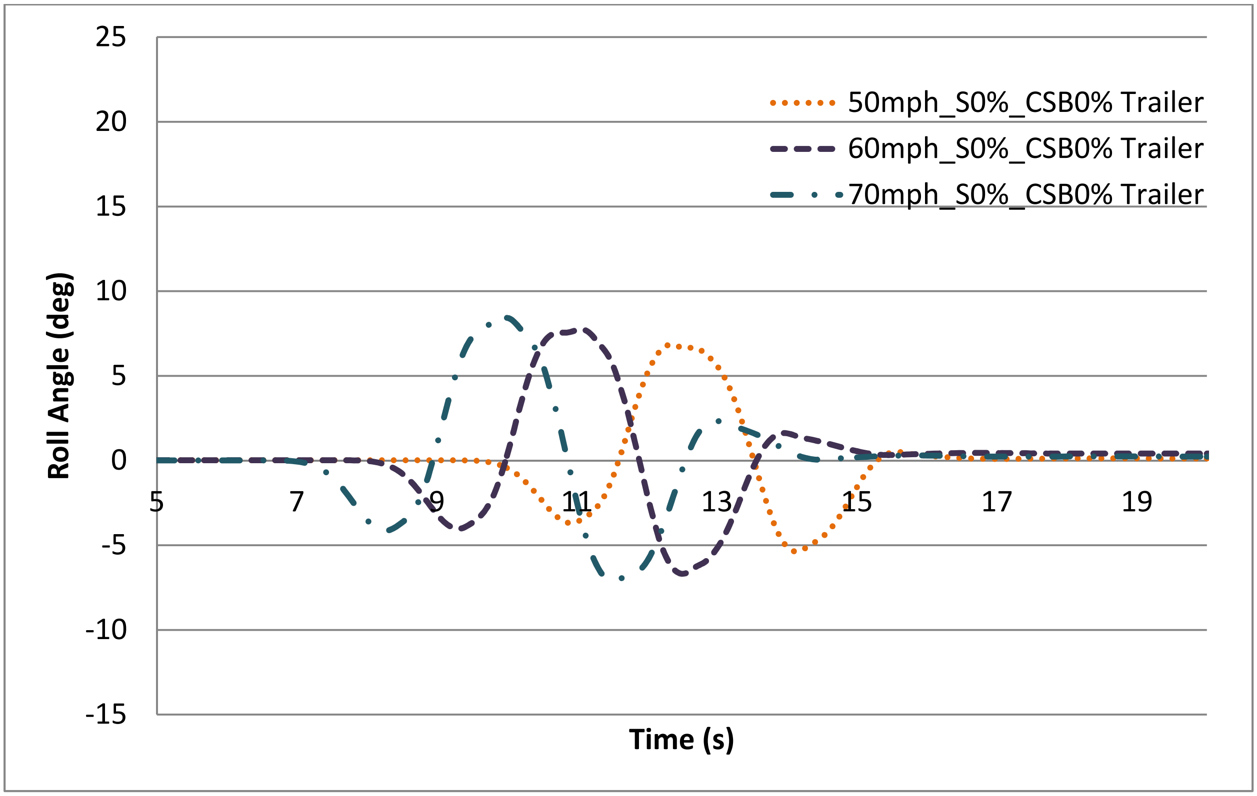
TABLE 3 shows the primary measures of interest output from TruckSim for the simulations of a tractor/single-van-trailer truck tested for the full traversal severe departure vehicle trajectory; the table specifies the superelevation, cross-slope break, and speed input to TruckSim. TABLE 3 indicates the vehicle recovered from each maneuver and displays the maximum negative and positive roll angles on the vehicle. FIGURE 5 shows a graph of the roll angles experienced by the tractor unit and trailer unit.

TABLE 3 Summary of TruckSim Results for a Tractor/Single-Van-Trailer Truck in Base Condition

Speed (mph)	50	60	70
Recover (Yes/No)	Yes	Yes	Yes
Max Neg Roll Angle (- deg)	-5.374	-6.684	-7.137
Max Roll Angle (+ deg)	6.846	7.48	8.425
NOTE: Base condition is a tangent with 0% superelevation and 0% cross-slope break			



(a) Tractor Unit



(b) Trailer Unit

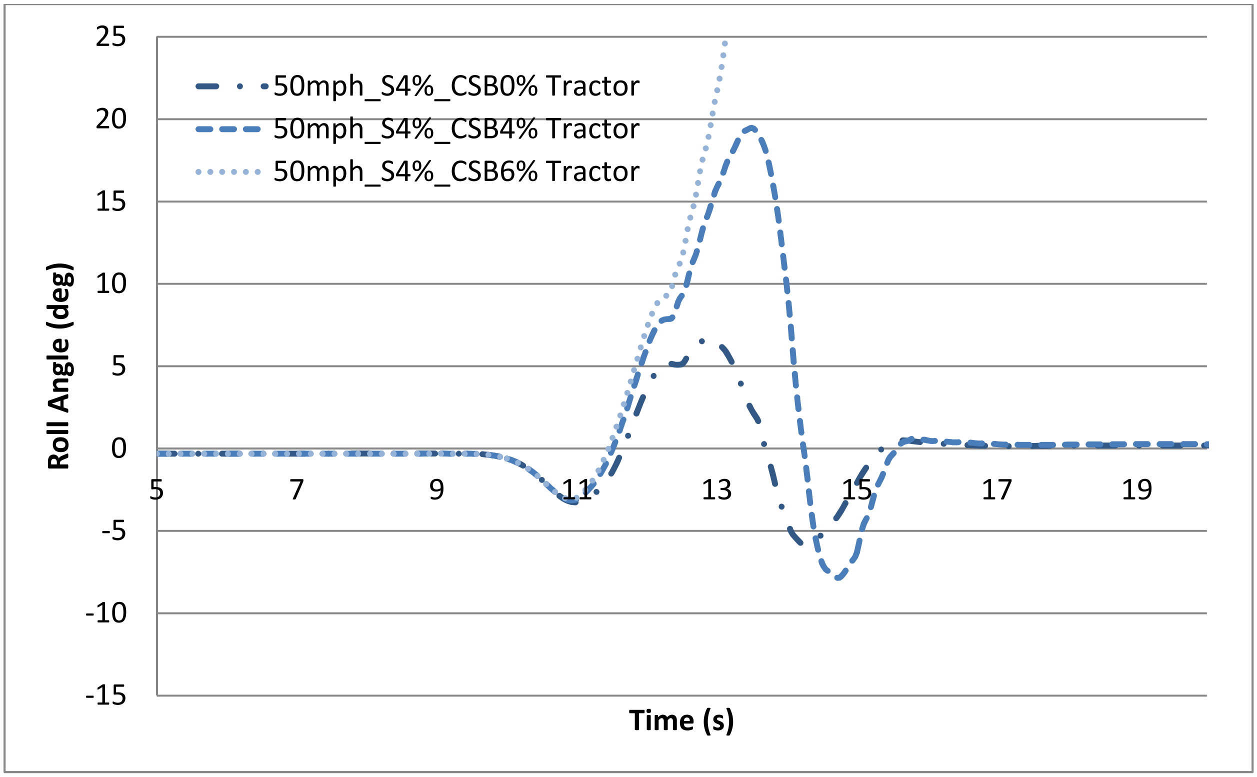
FIGURE 5 Roll angle of tractor unit and trailer unit in base condition.

TABLE 4 shows the primary measures of interest output by TruckSim for the simulations of a tractor/single-van-trailer truck tested for the full traversal severe departure vehicle trajectory and horizontal curvature for design speeds of 50 and 60 mph and superelevation of 4 percent. Cross-slope break values of 0, 4, and 6 percent were tested. Simulations were run until reaching a scenario in which the vehicle did not recover. For a speed of 60 mph, the vehicle failed to recover at a cross-slope break of 4 percent; at 50 mph, the non-recovery threshold was 6 percent. FIGURE 6 shows graphs of the roll angles experienced by the tractor unit and trailer unit for the simulations at 50 mph. The screenshots in FIGURE 7 were taken at the time when the vehicle experienced the maximum roll angle of either unit, and they show the influence of the cross-slope break at prescribed times during the full traversal severe departure maneuver.

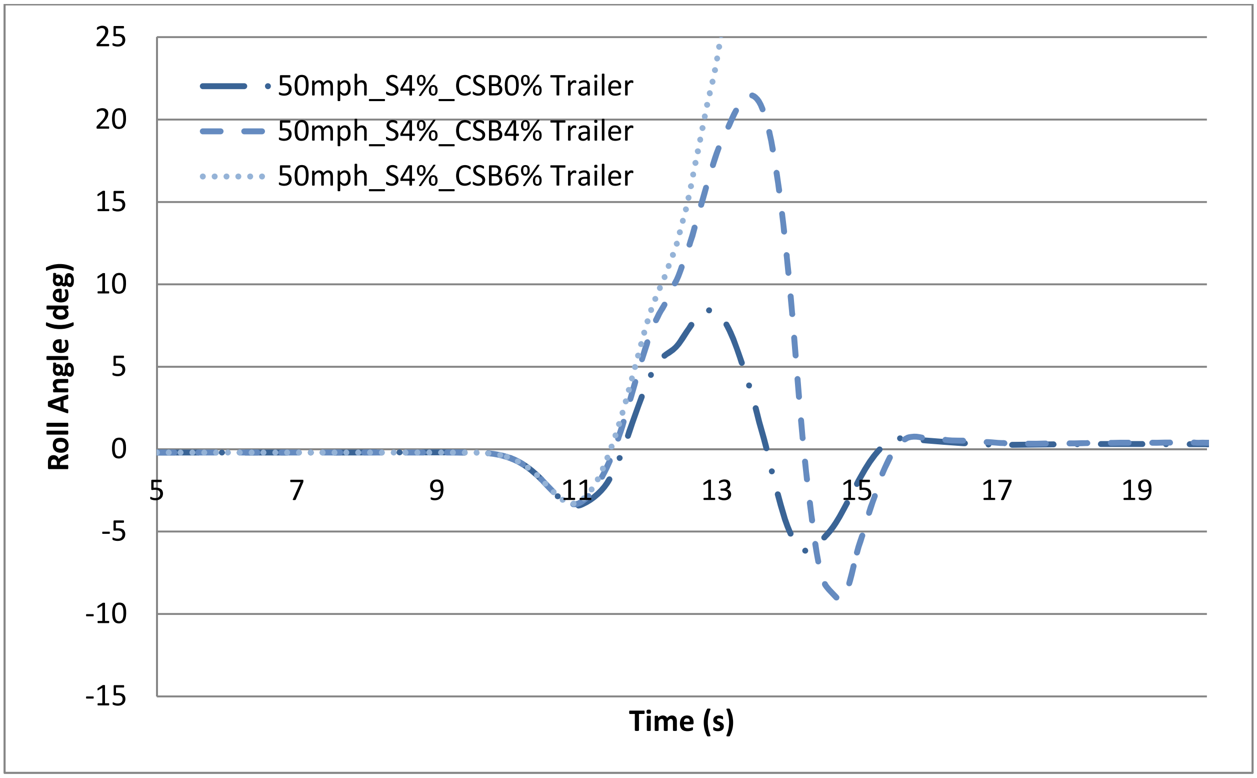
TABLE 4 Summary of TruckSim Results for Tractor/Single-Van-Trailer Truck Traversing Minimum Radius Curves with 4% Superelevation

Cross-Slope Break	0%		4%		6%	
Speed (mph)	50	60	50	60	50	60
Curve Radius (ft)	926	1,500	926	1,500	926	1,500
Recover (Yes/No)	Yes	Yes	Yes	No	No	NA[a]
Max Neg Roll Angle (- deg)	-6.168	-8.702	-9.121	NA	NA	NA
Max Roll Angle (+ deg)	8.429	11.812	21.479	NA	NA	NA

[a] NA = not applicable



(a) Tractor Unit



(b) Trailer Unit

1 **FIGURE 6 Roll angle of tractor unit and trailer unit at 50 mph on minimum radius curve**
2 **with 4% superelevation.**

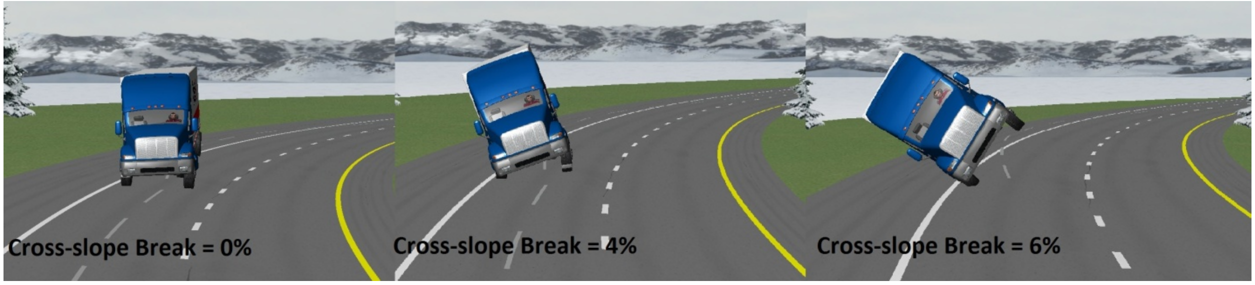


FIGURE 7 Illustration of maximum roll angle of tractor single-van trailer truck from TruckSim at 50 mph on minimum radius curve with 4% superelevation.

Researchers also simulated a tractor/single-van-trailer truck for the full traversal severe departure path and horizontal curvature for design speeds of 60 and 70 mph and a 6 percent superelevation. For speeds of 60 and 70 mph, the non-recovery thresholds were 4 and 6 percent, respectively.

Several insights drawn from the preliminary simulations that helped to select the final combinations of simulation scenarios tested were as follows:

- Vehicle stability following an encounter with a cross-slope break is likely highly dependent upon the defined vehicle departure trajectory/path.
- The observed roll angle trends help in interpreting results even if the vehicle successfully completed the maneuver without rolling over.
- There is no clear indication concerning the relationship between the interaction of vehicle speed and cross-slope break and vehicle stability.

Simulation Scenarios

To evaluate design criteria for pavement/shoulder cross-slope breaks, simulation scenarios were tested for the following values of critical geometric design elements and variables (although not all possible combinations were simulated):

- Cross-Slope Break
    - 4, 6, and 8 percent
    - 10 percent (as necessary)
- Superelevation
    - 4, 6, and 8 percent
- Vehicle Type
    - Tractor/single-van-trailer truck (~80,000 lb), ballast CG = 73 inches
    - Tractor/tanker-trailer truck (~80,000 lb, fully loaded), ballast CG = 81 inches
    - Tractor/double-van-trailer truck (~80,000 lb), ballast CG = 73 inches
        - Simulated selected scenarios to determine if behavior is consistent with tractor/single-van-trailer truck
- Vehicle Speed
    - 30, 50, and 60 mph
    - 70 mph (as necessary)
- Vehicle Departure
    - Partial and full traversal moderate departures

SUMMARY OF SIMULATION RESULTS

A total of 106 simulation scenarios were tested involving the partial and full traversal moderate departure vehicle trajectories, including 75 simulation scenarios for the tractor/single-van-trailer truck, 20 simulation scenarios for the tractor/tanker-trailer truck, and 11 simulation scenarios for the tractor/double-van-trailer truck. For each simulation, the stability of the vehicle was assessed based on the maximum positive roll angle and whether the vehicle recovered from the maneuver. Simulation results for the full traversal severe departure vehicle trajectory are not summarized here as this maneuver was simulated to verify that the vehicle dynamics simulation model was functioning properly and that vehicle rollovers did result in some cases. The results from the full traversal severe departure simulations were not directly considered when making decisions regarding design criteria for pavement/shoulder cross-slope breaks. However, it is important to note that several of the scenarios simulated represented a tractor/single-van-trailer truck for the full traversal severe departure vehicle trajectory with conditions very similar to the interchange ramp where the 2009 tanker truck crash occurred in Indiana, and the vehicle rolled over under those conditions, further verifying the validity of the simulation results.

Tractor/Single-Van-Trailer Truck Simulations

TABLE 5 summarizes the most critical roll angle results for the tractor/single-van-trailer truck simulations. Researchers observed the following characteristics of maximum roll angle in the moderate departure scenarios:

- It increased with an increase in the cross-slope break.
- It decreased with an increase in superelevation.
- It decreased with an increase in vehicle speed. This was primarily attributed to the use of larger design radii for the horizontal curves as design speeds increased, which is intended to provide additional stability to faster vehicles.

TABLE 5 Summary of Critical Results for Tractor/Single-Van-Trailer Truck

Vehicle	Tractor/Single-Van-Trailer Truck	
Vehicle Trajectory	Partial Traversal Moderate Departure	Full Traversal Moderate Departure
Largest Roll Angle (deg)	4.46	8.51
Superelevation (%)	4	4
Cross-Slope Break (%)	10	10
Speed (mph)	50	30
Recovery	All Cases	All Cases

Tractor/Tanker-Trailer Truck Simulations

Results from simulations for the tractor/single-van-trailer truck were used to select the simulation scenarios for the tractor/tanker-trailer truck, focusing on combinations with the greatest potential for rollover. TABLE 6 summarizes the most critical roll angle results for the tractor/tanker-trailer truck simulations. The partial traversal moderate departure vehicle trajectory was simulated for eight scenarios, using combinations of 6 or 8 percent cross-slope break, 4 or 6 percent superelevation, and 50 or 60 mph; the vehicle recovered in all eight scenarios. The vehicle also recovered in all full traversal moderate departure scenarios, which tested the eight combinations for partial traversal moderate departure plus 30- and 70-mph speeds for 8 percent cross-slope break and a 10 percent cross-slope break at 30 mph and 4 percent superelevation. Trends between roll angle and other variables were the same as those for the tractor/single-van-trailer truck.

TABLE 6 Summary of Critical Results for Tractor/Tanker-Trailer Truck

Vehicle	Tractor/Tanker-Trailer Truck	
Vehicle Trajectory	Partial Traversal Moderate Departure	Full Traversal Moderate Departure
Largest Roll Angle (deg)	4.06	9.76
Superelevation (%)	4	4
Cross-Slope Break (%)	8	10
Speed (mph)	50	30
Recovery	All Cases	All Cases

Tractor/Double-Van-Trailer Truck Simulations

Investigation of the dynamic behaviors of the tractor/double-van-trailer truck began by selecting simulation scenarios to determine if the stability behavior of the tractor/double-van-trailer truck was similar to that of the tractor/single-van-trailer truck. Since the full traversal moderate departure scenarios yielded higher roll angles for the tractor/single-van-trailer and the tractor/tanker-trailer trucks than the partial traversal moderate departure scenarios, only the full traversal moderate departure vehicle trajectory scenarios were considered in the simulation combinations.

The tractor/double-van-trailer truck recovered from the departure maneuver and returned to the travel lane successfully for all simulation scenarios conducted with a full traversal moderate departure vehicle trajectory. The tractor/double-van-trailer truck experienced higher roll angles than the tractor/single-van-trailer truck. The largest positive roll angle for the tractor/double-van-trailer truck was 9.91 degrees for the scenario with 10 percent cross-slope break, 4 percent superelevation, and 50 mph.

SUMMARY OF KEY FINDINGS

The primary results of the vehicle dynamics simulation modeling were as follows:

- The maximum roll angles for full traversal moderate departures were larger than for partial traversal moderate departures. This was expected based on the results of previous research (*4*).
- All of the moderate departure scenarios, both partial and full traversal, resulted in recovery of the vehicles (i.e., none of the vehicles rolled over during the moderate departure simulation scenarios).
- Maximum roll angles increased as the cross-slope break increased, and maximum roll angles decreased as the superelevation increased. For the moderate departures, the maximum roll angles decreased as speed increased. This was attributed to the increase in the design radius, which improves stability of faster vehicles.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

Based upon the simulation results for the tractor/single-van-trailer truck, the fully-loaded tractor/tanker-trailer truck, and the tractor/double-van-trailer truck for the partial and full traversal moderate departure vehicle trajectories, there is no evidence to suggest the need to reduce the threshold value of 8 percent as the maximum recommended cross-slope break. Of the three truck types evaluated, none rolled over in the simulation scenarios for the partial traversal moderate departure vehicle trajectory, nor the full traversal moderate departure vehicle trajectory, even when the cross-slope break was as high as 10 percent. Thus, there is some evidence to suggest that the recommended maximum cross-slope break could be increased to 10 percent. In particular, this may be possible for curves with higher superelevations, as vehicle dynamics simulation modeling showed that maximum roll angles decreased with increases in superelevation. However, this potential change to AASHTO’s design policy for pavement/shoulder cross-slope breaks on the outside of horizontal curves is not recommended as the current design policy with a maximum of 8 percent for the pavement/shoulder cross-slope break is the more conservative approach and because the scenario for tanker trucks with sloshing liquid could not be evaluated.

When the capabilities of vehicle dynamics models become sophisticated enough to simulate the dynamic effects of liquid sloshing in a tanker trailer, further research to more accurately incorporate tractor/tanker-trailer trucks in the vehicle dynamics simulation analysis is recommended. It would also be desirable to substantially increase the sample size of the dataset used in the detailed crash-based safety analysis so more meaningful results could be determined and a crash-based analysis could be factored into the design recommendations.

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 3-105, “Design Guidance for Interchange Loop Ramps” as part of Phase III – Assessment of Pavement/Shoulder Cross-Slope Breaks.

REFERENCES

1 National Transportation Safety Board. Rollover of a Truck-Tractor and Cargo Tank Semitrailer Carrying Liquefied Petroleum Gas and Subsequent Fire, Indianapolis, Indiana, October 22, 2009. NTSB/HAR-11/01. Washington, DC. 2011. http://www.ntsb.gov/investigations/AccidentReports/Reports/HAR1101.pdf

2 American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*. Washington, DC. 2011.

3 American Association of State Highway and Transportation Officials. *Roadside Design Guide*. Washington, DC. 2011.

4 Glennon, J.C., T.R. Neuman, R.R. McHenry, and B.G. McHenry. *HVOSM Studies of Cross-Slope Breaks on Horizontal Curves*. Federal Highway Administration, Contract No. DOT-FH-11-9575. Washington, DC. 1981.

5 Glennon, J. C., B.G. McHenry, and T.R. Neuman. *HVOSM Studies of Highway Cross-Slope Design*. FHWA-RD-84-006. Federal Highway Administration, Contract No. DOT-FH-11-9575. Washington, DC. 1983.

6 Glennon, J.C., and G.D. Weaver. “Highway Curve Design for Safe Vehicle Operations.” In *Highway Research Record 371*. Transportation Research Board. Washington, DC. 1972.
7 Rice, R.S. and F. Dell’Amico. *An Experimental Study of Automobile Driver Characteristics and Capabilities*. Calspan Report No. ZS-5208-K-1. Calspan Corporation. Buffalo, NY. March 1974.
8 Maeda, T., N. Irie, K. Hidaka, and H. Nishimura. “Performance of Driver-Vehicle System in Emergency Avoidance.” *International Automotive Engineering Congress and Exposition.* Society of Automotive Engineers. Detroit, MI. 1977.
9 Kim, J.-H., S. Hayakawa, T. Suzuki, K. Hayashi, S. Okuma, N. Tsuchida. “Modeling of Driver's Collision Avoidance Maneuver Base on Controller Switching Model.” *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, *35* (6), 1131-1143. IEEE Systems, Man, and Cybernetics Society. New York, NY. 2005.
10 Harwood, D.W., D.J. Torbic, K.R. Richard, W.D. Glauz, and L. Elefteriadou. *Review of Truck Characteristics as Factors in Roadway Design*. NCHRP Report 505. National Cooperative Highway Research Program. Washington, DC. 2003.
11 Torbic, D.J., M.K. O’Laughlin, D.W. Harwood, K.M. Bauer, C.D. Bokenkroger, L.M. Lucas, J.R. Ronchetto, S. Brennan, E. Donnell, A. Brown, T. Varunjikar. *Superelevation Criteria for Sharp Horizontal Curves on Steep Grades*. NCHRP Report 774. National Cooperative Highway Research Program. Washington, DC. 2013.
12 TruckSim 8.1, *Mechanical Simulation*, Ann Arbor, MI, December 2011.
13 American Association of State Highway and Transportation Officials. *Manual for Assessing Safety Hardware, First Edition*. Washington, DC. 2009.