Evaluation of Vehicle Dynamics for Single Unit Trucks on Sloped Roadsides and Medians

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ABSTRACT

There is increasing deployment of barriers on sloped surfaces for various reasons. The crashworthiness of barriers is, however, only ascertained for installation on level surfaces. There has been analysis of the vehicle dynamics effects of vehicle-to-barrier interfaces on sloped surfaces, but there have been no reported analyses of the vehicle dynamics of trucks traversing sloped surfaces. In this effort, the dynamics of a standard single unit truck (SUT) on a mild 6:1 sloped surface are evaluated to gain insights into the effect of the truck-to-barrier interface. The analysis addresses both roadside and median conditions. The effects of the vehicle departure angles and speed are investigated. The results are compared to the level surface case and the vehicle dynamics for an 8,000 kg and a 10,000 kg single-unit truck.
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BACKGROUND
Recent efforts to develop guidelines for effective placement of cable median barriers on sloped terrain have found that dynamic effects on the vehicle can have significant implications for the effectiveness of any barrier system [1-5]. In these efforts, the dynamic effects of various vehicles traversing slopes were analyzed for varying speeds and angles for cars and pick-up trucks. Since trucks make up a significant portion of traffic, the question of vehicle dynamics effects for single-unit trucks (SUT) arose. Since limited data was found for truck dynamics on slopes, this study was undertaken to generate vehicle dynamics data for single unit trucks following the same approach that was used to evaluate the effects for other vehicles. The results provide a basis for analyzing the potential effectiveness of barriers installed on similar slopes for SUTs.

This analysis was undertaken by the staff of the George Washington University (GWU) National Crash Analysis Center (NCAC) under a contract with the Federal Highway Administration (FHWA).

OBJECTIVE
The objective of this analysis was to generate vehicle dynamics data for single unit trucks (SUTs) traversing 6:1 unbounded (open) slopes and v-shaped medians to generate interface trace plots that could be used to assess potential interface effectiveness of barriers placed on such slopes.

APPROACH
The approach used to conduct this analysis was similar to that used in previous studies of the vehicle dynamics effects for cars and pick-up trucks. Key aspects of the analyses included:

- Use of the HVE software to analyze vehicle dynamics by applying standard physics equations to relate the influences of vehicle weight, wheelbase, suspension, and dimensions for varying speeds and departure angles to trajectories. This software package includes a broad library of validated models that reflect the fundamental features of common vehicles, including SUTs.

- The generation of trajectory (trace) plots that reflect the position of the potential vehicle interface area as it traverses a sloped surface reflecting the suspension response of the vehicle.

- Comparison of the trace envelopes to the face area of a barrier placed on the slope allows for the determination of its potential effectiveness. A barrier that is too low may lead to overrides and a barrier too high may allow underrides.

- In this analysis, 6:1 slopes for an unbounded roadside slope and a v-shaped median are considered. The latter is important since new effects are introduced when the vehicle encounters the up slope condition.

It is important to note the range of conditions considered and the underlying assumptions used in this analysis. These included:

- Road Departure Parameters:
  - Road departure angles of 5, 10, and 15 degrees
  - Road departure speeds of 31, 50, and 55 mph (50, 80, and 90 km/h)

- Vehicles Considered:
  - SUT 8000S (8,000 kg)
  - SUT 10000S (10,000 kg)
  - Pick-up truck (2,000 kg)
• Assumptions:
  o The roadside or median surface is firm and there is little or no furrowing (i.e., ploughing) by the tires.
  o Vehicle paths are essentially straight (no driver inputs).
• Sloped Surface Profiles:
  o The roadside has a 6:1 slope for a width of 100 feet. There is a 6% slope across a 6 foot wide shoulder prior to the slope (Figure 1).
  o The median profile (Figure 2) has a 48 foot wide, v-shaped median (edge-of-shoulder to edge-of-shoulder). The distance between the opposing lanes of traffic is 60 feet with 6 foot shoulders at an initial 8:1 side slope up to the beginning of the median. The median has a 6:1 slope that extends 24 feet to a low point before beginning upward at a similar slope. The cross section is symmetrical. There exist many other median configurations, but this was selected to allow comparison with data generated for other types of vehicles.
  o A barrier might be placed somewhere across this median.

![Figure 1: Roadside Slope Conditions Assumed for the Analyses](image1.png)

![Figure 2: Basic Sloped Surface Profile for Medians](image2.png)

**TRACES OF CRITICAL INTERFACE POINTS**
Since finite element crash simulations take a considerable amount of time to run, the Human Vehicle Environment (HVE) software by Engineering Dynamics Corp. was used to allow a quicker analysis [6]. The HVE software includes technical descriptions for various vehicles, including single-unit trucks. The software replicates the dynamics of each vehicle for the terrain it is traversing. For this effort, surfaces with mild 6:1 slopes were analyzed including v-shaped medians and single slope roadsides.
The vehicle dynamics simulations computed the trajectories of points on the vehicle as it traverses a sloped median on a diagonal path. In these analyses two points were defined for each type of vehicle to represent the primary interface (engagement) region on the vehicle. These points are labeled 1 and 2 on Figure 3. If one is standing in the center of the median downstream from the point the vehicle leaves the roadway, the trace of points 1 and 2 would be seen as the blue lines in Figure 4.

These same data points can be plotted on a diagram of the median cross section (as shown in the lower part of Figure 4). It can be noted that in moving from left to right, after passing the breakpoint between the shoulder and the median, the vehicle will be airborne or at least have a low compression load on its suspension system. At some point the vehicle will land (or return to a distribution of weight on all wheels), and the suspension will compress to absorb the load. As the vehicle continues its movement across the median there will be a rebound of the suspension as it dissipates energy. Thus, as the vehicle traverses the median the height of its interface area will vary depending on the state of the vehicle’s suspension system and the slopes of the median. Effective lateral placement of a barrier involves finding the locations where the vehicle’s interface area matches the barrier’s face heights. For median applications, finding these locations is complicated by the need to have an effective interface for impacts from either direction.

The study considered two different types of vehicles typically found on U.S. highways: a 2000P vehicle, Chevy C2500 pick-up truck; and a Ford F-700 single-unit truck (at weights of 8,000 kg and 10,000 kg). The specific weight, size, frontal geometry, and suspension system characteristics of these vehicles were incorporated into the vehicle dynamics analysis. Additionally, since vehicles can leave the roadway at varying speeds and angles, the analysis considered initial speeds of 30 to 62 mph (50 to 100 km/h) and impact angles of 5 to 25 degrees. The vehicles crossed the median on a diagonal as shown in Figure 3.

ROADSIDE SLOPES ANALYSES
To determine the vehicle dynamics effects for SUTs on a single slope, similar analyses were undertaken for a constant 6:1 slope condition that extended 100 feet from the edge of the shoulder. It was assumed that there would be a 6 foot wide shoulder between the traveled way and the beginning of the slope. The shoulder was assumed to have a 6% slope down from the traveled way.

Figure 5 shows the resulting normalized trace envelope for an 8,000 kg SUT moving at 100 km/h from left to right for departure angles of 5, 15, and 25 degrees. The data was normalized by translating the actual height of the trace points to a horizontal plane to facilitate comparisons. The color-coded shaded bands reflect the trace envelopes for the different departure angles considered. The yellow lines
represent the bounds of a trace envelope for this vehicle traversing level terrain. Thus, where the bands rise above or below the yellow lines, the vehicle will interface the barrier at a higher or lower position relative to level terrain. Similarly, for the bands falling below the lower yellow line, the vehicle’s frontal region will be lower.

It can be readily noted that for all angles there are peaks (or bulges) above the top yellow line for all three departure angles from the point at -34 feet from the centerline of the graph. The peaks get higher as the departure angle gets sharper. This is the result of the vehicle being at least partially airborne after it leaves the shoulder. There is a drop farther across the graph where the vehicle impacts the slope again. This effect is more pronounced where the spring response is the greatest. This again occurs for the sharpest departure angle.

![Normalized Trajectories](image)

**Figure 5:** Normalized Trace Envelopes for an SUT Traversing the Roadside Slope (from left to right) for Departure Speed of 100 km/h and Departure Angles of 5, 15, and 25 Degrees

Figure 6 depicts the effect of departure speed on the trace envelopes for the same vehicle. A similar effect is noted with the greatest degree of effect associated with the higher speeds.

Assessments of potential differences in barrier effectiveness between SUTs and a pick-up truck can be made by comparing the trace envelope at the lateral position of the barrier on this slope in Figure 7. In this graph, the green band represents the trace envelope for an 8,000 kg SUT. The red band represents the trace envelope for a 2000 kg pick-up truck (test vehicle for NCHRP 350 crashworthiness criteria). The broader face of the SUT results in a wider overall band, but it can be noted that high and low points occur at different positions for the trajectory conditions reflected here. If there is sufficient overlap of the trace envelopes and the barrier face, then it can be assumed that the barrier will be effective, subject to the assumptions associated with this analysis.
Figure 6: Normalized Trace Envelopes for an SUT Traversing the Roadside Slope (from left to right) for Departure Speeds of 50, 70, and 100 km/h and Departure Angle of 25 Degrees

Figure 7: Normalized Trace Envelopes Comparing an SUT and 2000kg Pick-up Truck Traversing the Roadside Slope (from left to right) for Departure Speed of 100 km/h and Departure Angle of 25 Degrees
In Figure 8, it is interesting to note the trace envelopes for the 8,000 kg SUT more closely resemble those for a 2,000 kg pick-up truck when both are at a speed of 100 km/h, but the departure angles are 15 and 25 degrees respectively. It can be noted that the lower bounds and general shape are similar, but the width of the trace band is, as expected, broader due to the differences in vehicle frontal heights. This is also interesting in the context of the differences in angles being similar to those for crashworthiness test level TL 4 with these vehicles.

Figure 9 shows the normalized trace envelopes for the SUT moving at 50, 80, and 100 km/h from left to right for all departure angles (5, 15, and 25 degrees). The full set of color-coded shaded bands would reflect the barrier coverage that would be needed to provide an interface for all conditions.

![Normalized Trajectories]

Figure 8: Normalized Trace Envelopes for an 8,000 kg SUT Traversing the Roadside Slope at a Departure Angle of 15 Degrees and a 2,000kg Pick-up at a Departure Angle of 25 Degrees with Both Vehicles at a Speed of 100 km/h
MEDIAN ANALYSIS

As noted earlier, vehicle dynamics analysis for medians requires considerations of the effects when the vehicle engages the opposite slope. The vehicle will go from a downward motion to an upward motion, and it may occur after the vehicle has been airborne. The vehicle’s suspension will be subjected to different levels of forces and will react in accordance.

Figure 10 shows the unidirectional, normalized trace envelopes for an 8,000 kg SUT moving at 90 km/h from the left to right for departure angles of 5, 10, and 15 degrees across a common v-shaped median 50 feet in width. The suspension compression and rebound is reflected in the traces on the right side of the median centerline. The implications of these trace envelopes relative to traveling over level surfaces is indicated where they fall above or below the yellow lines, which represent the trace for level conditions. While no attempt was made here to assess barrier effectiveness for medians, plotting lines representing the height of the barrier face in a similar fashion would reveal which lateral positions of the barrier might have potential interface problems.

Figure 11 provides a normalized plot of the trace envelope for the SUT moving at 50, 80, and 90 km/h from the left to right at a departure angle of 15 degrees. It can be noted for this vehicle that the traces are basically similar in magnitude across the range of speeds, but there are differences in where the effect takes place associated with the speed. For example, it is clear that the red trace for the slower speed shows an effect closer to the center of the median than does the blue trace for the highest speed.
Figure 10: Unidirectional Trace Envelopes for SUT Traversing a V-shaped Median at Angles of 5, 10, and 15 Degrees and a Speed of 90 km/h

Figure 11: Unidirectional Trace Envelopes for SUT Traversing a V-shaped Median at an Angle 15 Degrees and Speeds of 50, 80, and 90 km/h
Figure 12 provides a normalized comparison of the trace envelope for both the 8,000 and 10,000 kg SUTs moving at 90 km/h from the left to right for a departure angle of 15 degrees. The blue shaded band reflects the trace envelope for the 8,000 kg SUT and the green band the 10,000 kg SUT. The yellow lines represent the bounds of a trace envelope for this vehicle traversing level terrain. There are only slight variations noted for the differences in vehicle mass, mostly to the right of the centerline of the median reflecting the influence of the higher mass on the vehicle suspension response.

Similarly, Figure 13 provides a normalized comparison of the trace envelope for the 10,000 kg SUT moving at 90 km/h from either direction for a departure angle of 15 degrees. The blue shaded band reflects the trace envelope from one direction while the red band represents the trace envelope for the opposite direction. Since the median configuration is symmetrical, the trace envelopes are mirror images.

Figure 14 shows the combined trace envelopes for the 8,000 and 10,000 kg SUTs with departure angles of 5, 10, and 15 degrees and speeds of 50, 80, and 90 km/h. The bounds of all the individual trace envelopes would represent the overall trace envelope for SUTs traversing the median for the varying conditions.
Figure 13: Bi-directional Trace Envelopes for an 8,000 kg SUT Traversing a V-shaped Median at an Angle of 15 Degrees and Speed of 90 km/h

Figure 14: Combined Bi-directional Trace Envelopes for 8,000 and 10,000 kg SUTs Traversing a V-shaped Median at Angles of 5, 10, and 15 Degrees and Speeds of 50, 80, and 90 km/h
It is useful to consider the differences in the combined trace enveloped between SUTs and other vehicles. Figure 15 compares the combined trace envelope for the 8,000 kg and 10,000 kg SUTs and a 2,000 kg pick-up truck for the range of speeds and angles. The red band represents the trace envelope for a 2,000 kg pick-up truck and the green band represents the corresponding trace envelope for the SUTs. It can be noted that the SUTs cast a wider trace envelope due to their size, but there are some similarities in the lower bounds close to the center of the median, but variations moving outward.

Figure 16 is similar, but it includes a combined trace envelope that includes not only the pick-up truck, but an 820 kg small car and a 1,600 kg mid-sized sedan. Due to the differences in vehicle dynamics for the cars, the red band is broader and slightly different on the lower bound, than that for just the pick-up truck.

![Figure 15: Combined Bi-directional Trace Envelopes for 8,000 kg and 10,000 kg SUTs and 2,000 kg Pick-up Truck Traversing a V-shaped Median at Angles of 5, 10, and 15 Degrees and Speeds of 50, 80, and 90 km/h](image)
SUMMARY & CONCLUSIONS

This effort successfully used available vehicle dynamics software to analyze the trajectories of SUTs on sloped roadsides and medians. This was necessary since little existing data about the dynamics of single unit trucks was found in the literature. A series of trace plots were generated to reflect the positions of the frontal area of SUTs while traversing the slopes to provide a basis for understanding the potentials effectiveness of barrier placement. It was noted that:

- The size, weight, and design characteristics of single unit trucks are significantly different than cars or sport utility vehicles.
- Vehicle dynamics analysis tools have the capabilities to analyze the dynamics of single unit trucks traversing sloped terrain.
- This research analyzed vehicle dynamics for various cases of SUTs traversing v-shape medians with mild 6:1 side slopes.
- A distinctive dynamic response can be noted in the trace envelopes for the SUTs.
- The height of the frontal area for an SUT results in a broader trace envelope.
- SUTs tend to have a less pronounced dynamic effect for variations in mass, departure angle, and speed.
- Comparisons with trace plots for the same slope conditions for passenger cars and pick-up trucks were generated to understand the degree of differences.
- The results are potentially useful in considering the design and placement of barriers for impacts with SUTs.
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