Analyses of Vehicle Trajectories on 4:1 Single Slope Roadside Terrain

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This working paper summarizes recent efforts and findings derived from NCAC research. It is intended to solicit feedback on the approach, scenarios analyzed, findings, interpretations, and implications for practice reported by the research team. The statements contained herein do not necessarily reflect the views or policy of the FHWA. Please forward comments or questions to the authors noted above. These efforts will ultimately be documented and made available to advance research efforts related to this topic and guidance for practice.

ABSTRACT

Barrier placement practice has discouraged the use of barriers on all but gentle slopes adjacent to the roadway. Testing has been done on level surfaces to facilitate comparison of results from various tests and promote repeatability of tests. With limited space available for highways, particularly as they are widened, the feasibility of placing barriers on slopes has gotten more attention. Much of this has stemmed from efforts to deploy cable barrier systems to highway medians to reduce cross median crashes. Research by the FHWA and others has been focused on understanding the effects of slopes on the trajectories of vehicles as a first step in determining which slopes can accommodate barriers and where on the slope they will be effective. This analysis was generated using vehicle dynamics analysis tools to trace the interface region on the front of typical vehicles. The results indicate the effects of the vehicle features, particularly suspension systems, for road departures at varying speeds and angles. Data was generated for a range of vehicles for 4:1 slopes, which are generally considered the maximum traversable slope.
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INTRODUCTION
Barrier placement practice has discouraged the use of barriers on all but gentle slopes adjacent to the roadway. Testing has been done on level surfaces to facilitate comparison of results from various tests and promote repeatability of tests. With limited space available for highways, particularly as they are widened, the feasibility of placing barriers on slopes has gotten more attention. Much of this has stemmed from efforts to deploy cable barrier systems to highway medians to reduce cross median crashes. Research by the FHWA and others has been focused on understanding the effects of slopes on the trajectories of vehicles as a first step in determining which slopes can accommodate barriers and where on the slope they will be effective.

APPROACH
In this analysis, vehicle dynamics simulations were performed to assess a vehicle’s trajectory as it crosses a sloped surface. Simulations were conducted with varied vehicles, speeds, and orientations (approach angles). A total of 45 simulations were performed. Three different speeds were included in the analysis: 50, 70, and 100 km/h (31, 43, and 62 mph). Five vehicle approach angles were included in the matrix of simulations (5, 15, 25, 35, and 45 deg). The slope condition was the same for all cases.

TERRAIN CONDITIONS
The surface used in the simulations was a 4:1 down slope. The width of the sloped section was chosen to be 9.75m (32ft). This profile is shown in Figure 1. It was assumed that the slope had a firm surface to limit furrowing by the vehicle tires into the surface.

![Figure 1 – Single 4:1 Slope Profile](image-url)
VEHICLE CHARACTERISTICS
The vehicles analyzed included a Chevrolet C2500 pickup truck, a Ford Crown Victoria large sedan, and a Honda Civic small car. Characteristics of these models are presented Tables 1-3. Two points on the front of each vehicle were selected to depict the vehicle’s primary interface area. The two points are located at the leading (right-front) corner of the vehicle. The vertical locations of these two points were selected such that they can be used to identify whether or not there would be a good interface or engagement with the vehicle and a cable barrier (which offers the least engagement area). The first point was selected such that the cable is likely to go over the vehicle if the cable impacts the vehicle above this point. Similarly, the second point was selected such that the cable is likely to go under the vehicle if the cable impacts below this point. In the region between these two points, the cable will remain in contact with the vehicle during the impact. The locations of the two points for each of the three vehicles are presented in Tables 1-3. The vehicle dynamics analysis traced the positions of each of the points while the vehicle traversed the sloped section. Trajectory plots were generated for these points from the perspective of an observer downstream from the vehicle’s path.

RESULTS
The vehicle dynamics analyses generated trajectory data every tenth of a second and the data was subsequently plotted. The results from the simulations are presented for each of the three vehicles. For each vehicle the following trajectory plots are provided:

- Plot 1: Vehicle trajectory for a 25 degree road departure angle at 100 km/h
- Plot 2: Vehicle trajectories at 25 degrees for all speeds (50, 70 and 100 km/h)
- Plot 3: Vehicle trajectories at 100 km/h for all departure angles (5, 15, 25, 35, and 45 degrees)
- Plot 4: Vehicle trajectories at all analyzed speeds and angles

The shaded region in the plots shows the area where a cable would need to be to engage the vehicle at any lateral position on the sloped surface. These plots allow for the change in the height of the interface region on each vehicle while it traverses the slope. The “normal” height occurs on the upper level portion of each graph. At this point dynamic effects have not occurred. It can be noted that the height of the trace at a point about halfway down the slope in Exhibit 1 is almost twice that of normal, indicating that the vehicle is likely to be at least partially airborne. Near the base of the slope, the height is lower than the normal due to compression of the springs when the vehicle returns to the surface after being airborne. The range of trajectory paths presented here is an indication of the range of departure conditions that must be addressed to have barriers that will be effective for a range of vehicles and initial departure conditions.

SUMMARY AND CONCLUSIONS
In this effort, the terrain effects on vehicle trajectories were determined using vehicle dynamics analysis tools. These tools allowed the entry of data for specific vehicles that reflected differences in size, weight, suspension features, and other factors as well as the conditions under which the vehicle leaves the roadway (i.e., speed, angle) and the nature of the roadside. Two points representing the leading edge of the structural region on the front of three different vehicles was defined. The trace envelope projected by the trajectory of these points while the vehicle traverses the slope provides useful insights. The trace indicates the effects of the sprung mass of the vehicle and the relative position of the vehicle’s interface area relative to the surface. The former is useful in understanding more specifically the effects of slope, departure angle, and speed. The latter aspect is a critical metric for determining the lateral placement of the barrier to be effective.
The analysis was undertaken for the typical limiting slope condition, namely 4:1. It was observed that:

- The vehicle trace envelope does not follow the slope surface at the same position after leaving the road. It can be higher when the vehicle or particular tires become airborne or lower when the vehicle hits the surface and the suspension becomes compressed.
- Given that barriers typically have a constant height, there is a potential vehicle-to-barrier interface problem when the interface trace does not coincide with the barrier’s engagement area.
- The trajectory plots show a greater tendency for the vehicle to become airborne for larger vehicles and higher speeds.
- Trajectories are higher for the sharper departures angles and higher speeds.
- The trajectory plot is different for each vehicle at the same departure angle and speed due to the weight.

It can be readily noted that there is a challenge finding positions where a typical barrier can be effective for any given vehicle and departure condition. It gets more complicated trying to find the appropriate position and barrier design for the ideal case where the barrier would serve all vehicles and road departure conditions.
Table 1 – Characteristics of the C2500 Pick-up Truck

C2500 Pickup Truck:

Make: Chevrolet
Model: C-2500 pickup
Year: 1988-1999
Body Style: Fleetside

Mass: 2078 kg (4,582 lbs)
Roll Inertia: 556 kg m² (410 lb ft s²)
Pitch Inertia: 3829 kg m² (2824 lb ft s²)
Yaw Inertia: 4112 kg m² (3033 lb ft s²)

Total Length: 5.7 m (223 in)
Total Width: 2.0 m (79 in)
Total Height: 1.8 m (73 in)

CG X location: 2.39 m (94 in) - from forward most point on bumper
CG Y location: 0 m (0 in) - at center of Vehicle
CG Z Location: 0.728 m (28.7 in) – above Ground

Point 1 Location:
P1ₓ= 2.16 m (85 in) forward from C.G.
P1ᵧ= 0.89 m (35 in) to the right of C.G.
P1ₗ= 0.18 m (7 in) below C.G.

Point 2 Location:
P2ₓ= 2.10 m (83 in) forward from C.G.
P2ᵧ= 0.81 m (32 in) to the right of C.G.
P2ₗ= 0.28 m (11 in) above C.G.
<table>
<thead>
<tr>
<th>Make: Ford</th>
<th>Model: Crown Victoria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year: 1992-1997</td>
<td>Body Style: Sedan</td>
</tr>
<tr>
<td>Mass: 1722 kg (3,790 lbs)</td>
<td>Roll Inertia: 440 kg m² (325 lb ft s²)</td>
</tr>
<tr>
<td>Pitch Inertia: 3358 kg m² (2475 lb ft s²)</td>
<td>Yaw Inertia: 3448 kg m² (2541 lb ft s²)</td>
</tr>
<tr>
<td>Total Length: 5.36 m (211 in)</td>
<td>Total Width: 1.96 m (77 in)</td>
</tr>
<tr>
<td>Total Height: 1.52 m (60 in)</td>
<td>CG X location: 2.28 m (89.8 in) - from forward most point on bumper</td>
</tr>
<tr>
<td>CG Y location: 0 m (0 in) - at center of Vehicle</td>
<td>CG Z Location: 0.620 m (24.4 in) – above Ground</td>
</tr>
<tr>
<td>Point 1 Location:</td>
<td></td>
</tr>
<tr>
<td>P₁ₓ= 2.16 m (85 in) forward from C.G.</td>
<td></td>
</tr>
<tr>
<td>P₁ᵧ= 0.86 m (34 in) to the right of C.G.</td>
<td></td>
</tr>
<tr>
<td>P₁ᵢ= 0.13 m (5 in) below C.G.</td>
<td></td>
</tr>
<tr>
<td>Point 2 Location:</td>
<td></td>
</tr>
<tr>
<td>P₂ₓ= 2.16 m (85 in) forward from C.G.</td>
<td></td>
</tr>
<tr>
<td>P₂ᵧ= 0.86 m (34 in) to the right of C.G.</td>
<td></td>
</tr>
<tr>
<td>P₂ᵢ= 0.20 m (8 in) above C.G.</td>
<td></td>
</tr>
</tbody>
</table>
Table 3 – Characteristics of the Honda Civic Sedan

<table>
<thead>
<tr>
<th>Make</th>
<th>Honda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Civic</td>
</tr>
<tr>
<td>Year</td>
<td>1975-1979</td>
</tr>
<tr>
<td>Body Style</td>
<td>Hatch Back</td>
</tr>
</tbody>
</table>

Mass: 805 kg (1771 lbs)
Roll Inertia: 251 kg m² (185 lb ft s²)
Pitch Inertia: 1329 kg m² (980 lb ft s²)
Yaw Inertia: 1496 kg m² (1103 lb ft s²)

Total Length: 3.71 m (146 in)
Total Width: 1.49 m (59 in)
Total Height: 1.35 m (53 in)

CG X location: 1.57 m (62 in) - from forward most point on bumper
CG Y location: 0 m (0 in) - at center of Vehicle
CG Z Location: 0.56 m (22 in) – above Ground

Point 1 Location:
- $P_{1x} = 1.40$ m (55 in) forward from C.G.
- $P_{1y} = 0.66$ m (26 in) to the right of C.G.
- $P_{1z} = 0.15$ m (5 in) below C.G.

Point 2 Location:
- $P_{2x} = 1.40$ m (55 in) forward from C.G.
- $P_{2y} = 0.66$ m (26 in) to the right of C.G.
- $P_{2z} = 0.15$ m (6 in) above C.G.
TRAJECTORY PLOTS

Exhibit 1 – C2500 Pick-Up Trajectories for an Angle of 25 Degrees and a Speed of 100 km/h

Exhibit 2 – C2500 Pick-Up Trajectories for an Angle of 25 Degrees and Speeds of 50, 70, & 100 km/h

Exhibit 3 – C2500 Pick-Up Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and a Speed of 100 km/h

Exhibit 4 – C2500 Pick-Up Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and Speeds of 50, 70, & 100 km/h

Exhibit 5 – Crown Victoria Sedan Trajectories for an Angle of 25 Degrees and a Speed of 100 km/h

Exhibit 6 – Crown Victoria Sedan Trajectories for an Angle of 25 Degrees and Speeds of 50, 70, & 100 km/h

Exhibit 7 – Crown Victoria Sedan Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and a Speed of 100 km/h

Exhibit 8 – Crown Victoria Sedan Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and Speeds of 50, 70, & 100 km/h

Exhibit 9 – Honda Civic Sedan Trajectories for an Angle of 25 Degrees and a Speed of 100 km/h

Exhibit 10 – Honda Civic Sedan Trajectories for an Angle of 25 Degrees and Speeds of 50, 70, & 100 km/h

Exhibit 11 – Honda Civic Sedan Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and a Speed of 100 km/h

Exhibit 12 – Honda Civic Sedan Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and Speeds of 50, 70, & 100 km/h
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4:1 Drop - 32ft Width

Honda Civic
Angle: 25 deg
Speeds: 50, 70, 100 km/hr
Exhibit 11 – Honda Civic Sedan Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and a Speed of 100 km/h
Exhibit 12 – Honda Civic Sedan Trajectories for Angles of 5, 15, 25, 35, & 45 Degrees and Speeds of 50, 70, & 100 km/h