Prediction of the Sensitivity of Vehicle Dynamics to Highway Curve Geometrics by Using Computer Simulation

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The highway-vehicle-object-simulation model (HVOSM) was used to study vehicle responses and their sensitivity to various highway curve elements. After initial validation runs, a parameter study was conducted by using a simulated path of an inattentive driver. The highway curve and operational elements studied included vehicle speed, highway curve radius, length of curve, superelevation rate, superelevation runoff length, superelevation runoff distribution, presence of spiral transition, and presence of downgrade. The study revealed two significant results: (a) the dynamic response of vehicles traversing a highway curve is sensitive to speed; and (b) the addition of spiral transitions to highway curves dramatically reduces the friction demand of critical vehicle traversals.

One phase of the FHWA research project, "Effectiveness of Design Criteria for Geometric Elements," is presented in this paper. The project is a comprehensive effort aimed at quantifying aspects of highway design that have the greatest impact on highway safety.

The objectives of the research phase presented here are to

1. Demonstrate the applicability of the highway-vehicle-object-simulation model (HVOSM) as a tool for evaluating the dynamic response of vehicles traversing highway curves, and
2. Study the sensitivity of critical vehicle traversals to various highway curve design elements.

RESEARCH METHODOLOGY

HVOSM is a computerized mathematical model of a passenger vehicle that was originally developed by Cornell Aeronautical Laboratories and subsequently refined by Calspan Corporation (1). HVOSM simulates the dynamic response of a vehicle traversing a three-dimensional terrain configuration. The vehicle is composed of four rigid masses: sprung mass, unsprung masses of the left and right independent suspensions of the front wheels, and an unsprung mass that represents a solid rear-axle assembly.

The Roadside Design version of HVOSM currently available from FHWA is used in this study. Because the objective of these HVOSM tests is to study various dynamic response components, irrespective of available skid resistance, a high (0.8) friction factor was used. A 1971 Dodge Coronet was used as the test vehicle because it best represented the current population of passenger cars among the vehicles that have been modeled for HVOSM application. Certain modifications were made to perform the highway curve traversals and to interpret the appropriate dynamic responses:

1. Driver discomfort factor output,
2. Friction demand output,
3. Terrain table generator,
4. Driver model inputs (damping, steer velocity, steer initialization), and
5. Wagon-tongue path-following algorithm.

One significant aspect of the path-following algorithm is the length of the wagon-tongue or probe length. The wagon-tongue is attached to the center of gravity and extends in front of the vehicle parallel to its x-axis. A probe at the end of the wagon-tongue monitors the error from the intended path and activates the driver model inputs.

The probe length simulates the complex interaction that occurs as a driver sees the roadway ahead and responds to what is seen. Selection of a probe length, therefore, determines the type of driver being modeled. Very long probe lengths are indicative of ideal drivers who prepare for the curve well in advance. The resulting simulated behavior closely follows that described by the centripetal force equation, where the simulated vehicle path tracks almost exectly the center of the lane.

Moderate probe lengths create minor path corrections just preceding the curve and allow the vehicle to track in a near-optimum manner. Calculated friction values are somewhat higher than the values generated with the longer probe length.

Very short probe lengths represent either aggressive or inattentive driver behavior. Path corrections in response to the presence of the curve would come only as the vehicle actually enters the curve. The result is a dynamic overshoot at the beginning of the curve, where high lateral friction demand is generated by the vehicle, and the vehicle follows a distinctly noncircular path.

This discussion emphasizes the need to carefully define the driver behavior being modeled. Highly variable results can be obtained by running different probe lengths on the same simulated curve at the same speed.

INITIAL HVOSM STUDIES

Twelve initial HVOSM runs were made to demonstrate and verify that the model yields reasonable dynamic responses for curve traversals. These runs were made on unspiraled highway curves with the AASHO (2) superelevation runoff length distributed at 70 percent on tangent and 30 percent on curve. The idea was to select a long probe length that would allow the vehicle to track the center of the lane with little path deviation. The resulting vehicle dynamics given by HVOSM could then be compared with those predicted by the centripetal force equation.

The calculated and simulated dynamic responses for running the vehicle at design speed for the 12 test curves are given in Table 1. The calculated lateral acceleration ($V^2/127R$) and the simulated lateral acceleration are closely comparable for all tests. Also, the calculated tire responses $[(V^2/127R)-e]$ are comparable with the simulated tire responses.

It is interesting to note that, because of roll-angle, the driver discomfort factor (centrifugal acceleration acting on the driver) is always higher than the lateral acceleration on the tires. Therefore, the design f values in the AASHO process are not the centrifugal acceleration where the driver begins to feel discomfort, but represent the lateral friction on the tires that creates a higher threshold of driver discomfort.

Table 1. Initial HVOSM tests.

Speed (km/h)	Roadway Radius (m)	Super-elevation (m/m)	Calculated Lateral Acceleration ($V^2/127R$)	Calculated Tire Friction [($V^2/127R$)-e]	HVOSM Results Maximum Lateral Acceleration	Maximum Tire Friction	Maximum Driver Discomfort Factor
33	33	0.08	0.25	0.17	0.25	0.17	0.20
33	39	0.04	0.21	0.17	0.20	0.14	0.18
50	70	0.10	0.26	0.16	0.26	0.17	0.20
50	83	0.06	0.22	0.16	0.22	0.17	0.20
67	143	0.08	0.23	0.15	0.23	0.16	0.18
67	175	0.04	0.19	0.15	0.19	0.16	0.19
83	198	0.10	0.26	0.16	0.27	0.17	0.21
83	259	0.06	0.20	0.14	0.20	0.14	0.18
100	368	0.08	0.20	0.12	0.22	0.10	0.15
100	466	0.04	0.16	0.12	0.18	0.12	0.16
117	499	0.10	0.20	0.10	0.20	0.11	0.12
117	635	0.06	0.16	0.10	0.16	0.11	0.13

NOMINALLY CRITICAL VEHICLE OPERATIONS

With HVOSM verified for use on curve traversals, the model appeared to be a reasonable tool for studying traversals where the vehicle does not precisely follow the center of the lane. The purpose of this exercise was to use HVOSM to study the sensitivity of vehicle dynamics to varying curve and operational parameters.

It was first necessary to define a nominally critical level of driver behavior. Less-critical or near average behavior would result in simulations that tend to mirror dynamics predicted by the centripetal force equation. On the other hand, highly critical levels may not produce realistic results, and thus may not provide a useful basis for comparing variable geometrics.

The selection of an appropriate level of criticality was based on previous vehicle operations research. Studies by Glennon (3) in Texas indicated that most drivers exceed the AASHO design f by a nominal amount, and that some exceed it greatly. The subject report revealed that maximum path curvature was related to highway curvature for various percentiles of the driving population. For purposes of this study, the 95th percentile path was selected to represent nominally critical operations. This relation is

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

where R_v is the 95th percentile vehicle path radius (m) and R is the highway curve radius (m). By using this path, the critical f factors were calculated by substituting path curvature for highway curvature in the centripetal force equation for any design speed combination of highway curvature and superelevation.

With the establishment of the relation between highway curve parameters and nominally critical f factors, several preliminary HVOSM runs were made to select a probe length that best generated the intended critical operations. This probe length was

$$L = 0.25v \quad (2)$$

where L is the probe length (cm) and v is the forward velocity (cm/sec).

CRITICAL HVOSM STUDIES

With the probe length established, HVOSM could study the sensitivity of vehicle dynamics to various highway curve design and operational parameters under nominally critical path-following conditions. Of particular interest were

1. Vehicle speed,
2. Superelevation runoff length,
3. Superelevation runoff distribution,
4. Presence of spirals,
5. Length of spiral,
6. Presence of downgrade, and
7. Short curve lengths.

Twenty-four HVOSM runs were made by using six AASHO metricated curves. The results of these runs are given in Table 2. The conclusions from these studies are discussed below.

Vehicle Speed

The dynamic responses on any curve are sensitive to vehicle speed. Each of the six test highway curves was run at 20 km/h above design speed. The tire friction for this speed increment was quite sensitive for the lower design speed curves. For the 40 km/h design speed curve, the friction demand was simulated to be 0.52 compared with a design f of 0.16. These results could also be similarly predicted with the centripetal force equation (thus providing one more verification of the HVOSM methodology).

The implications of the test results for speed are significant. These implications suggest that an existing highway curve that is underdesigned for the prevailing operating speed could present a severe roadway hazard. This is particularly true for design speeds below 100 km/h. At these lower design speeds the actual vehicle operating speeds of 10 km/h or more above the curve design speed can be reasonably expected.

Superelevation Runoff Length

Superelevation runoff length was evaluated for 80 and 100 km/h design speeds by comparing the AASHO runoff length with one that was half as much. In this comparison the superelevation runoff length was distributed with 70 percent on the tangent and 30 percent on the curve.

The somewhat surprising result of these tests was that the shorter runoff length yielded smaller friction demands. The only identifiable explanation for this phenomenon is that the maximum friction demands take place in the initial part of the curve, where the shorter runoff length would provide slightly higher superelevation.

Superelevation Runoff Distribution

Superelevation runoff distribution was evaluated for 80 and 120 km/h highway curves that have AASHO

Table 2. Critical HVOSM tests.

Curve Radius (m)	Test Parameters: Maximum Superelevation (m/m)	Curve Design Speed (km/h)	Length of Superelevation Runoff (m)	Maximum Superelevation on Tangent (%)	Presence and Length of Spiral	Percent Grade	Operating Speed of Test Vehicle (km/h)	Results: AASHO Design f	HVOSM f
750	0.06	120	61	70	None	0	140	0.092	0.190
750	0.06	120	61	70	None	0	120	0.092	0.150
600	0.10	120	92	70	None	0	140	0.092	0.230
600	0.10	120	92	70	None	0	120	0.092	0.160
600	0.10	120	92	20	None	0	120	0.092	0.190
600	0.10	120	50	70	None	0	120	0.092	0.120
410	0.08	100	66	70	None	0	120	0.116	0.260
410	0.08	100	66	70	None	0	100	0.116	0.170
410	0.08	100	33	70	None	0	100	0.116	0.140
410	0.08	100	66	NA	AASHO	0	100	0.116	0.100
210	0.10	80	72	70	None	0	100	0.140	0.390
210	0.10	80	72	70	None	0	80	0.140	0.240
210	0.10	80	72	20	None	0	80	0.140	0.260
210	0.10	80	72	70	None	5	80	0.140	0.240
210	0.10	80	72	NA	AASHO	0	80	0.140	0.120
210[a]	0.10	80	72	70	None	0	80	0.140	0.200
210	0.10	80	72	20	None	5	100	0.140	0.430
130	0.08	60	50	70	None	0	80	0.152	0.400
130	0.08	60	50	70	None	0	60	0.152	0.200
130	0.08	60	50	70	None	5	60	0.152	0.210
130	0.08	60	50	NA	AASHO	0	60	0.152	0.120
50	0.10	40	50	70	None	0	60	0.164	0.520
50	0.10	40	50	70	None	0	40	0.164	0.200
50	0.10	40	50	70	None	5	40	0.164	0.200

Note: NA = not available.
[a]50-m curve length.

superelevation runoff lengths with 70-30 and 20-80 distributions.

As expected, the 70-30 distribution, where most of the superelevation transition is provided on the tangent, produces somewhat smaller friction demands. The differences can be explained almost entirely by the difference in superelevation in the initial part of the curve where the maximum friction demand is generated.

Presence of Spirals

The presence of spirals was evaluated for highway curves with design speeds between 60 and 100 km/h. The comparison was between highway curves with and without AASHO spirals.

This comparison provides the most dramatic results of the study. In all cases the presence of the spiral reduced the friction demand from a value significantly higher than the design f to one that was below the design f.

The reason for this dramatic result is readily evident. For the driver who is inattentive or for some other reason has limited notice of the upcoming curve, the spiral not only reduces the driver's absolute path error over time but requires less severe steering to correct for the desired path because the path of a spiral is less severe than the path of a circular curve.

Length of Spiral

Although the initial plan was to test a spiral that was twice the length of an AASHO spiral, this plan was not carried through after obtaining the dramatic results for the presence of AASHO spirals.

Presence of Downgrade

The presence of downgrades was evaluated for highway curve design speeds between 40 and 80 km/h. In comparing a 5 percent downgrade with level terrain, no difference was found in the friction demand.

Short Curve Lengths

Short curve lengths were evaluated by examining the difference between vehicular response to the approach to a curve (i.e., the dynamics of proceeding from tangent to curve) and the response to a very short curve. Short curves require continuous responses by the driver as he moves in and then out of the curve. A 50-m curve length of an 80 km/h design curve was selected for analysis.

The results of this test indicate that the short curve does not generate any greater dynamic responses than those found on a longer curve that has the same radius and vehicle speed.

SUMMARY

The critical analysis of highway curve design parameters provided two significant results. First, the dynamic response of vehicles traversing a highway curve are extremely sensitive to speed. This implies that existing highway curves that are severely underdesigned for prevailing highway speeds may present serious roadway hazards.

Second, it is significant to note that the addition of spiral transitions to highway curves dramatically reduces the friction demand of critical vehicle traversals.

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