Development of a Driver Vehicle Module for the Interactive Highway Safety Design Model

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Research, Development, and Technology
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FOREWORD

The Driver Vehicle Module (DVM) is a software tool that allows traffic engineers and highway designers to evaluate how a driver would operate a vehicle within the context of a specific roadway design and to identify whether conditions exist within that design that could result in loss of vehicle control. It was developed as a candidate evaluation module for the Interactive Highway Safety Design Model (IHSDM).

The DVM couples a vehicle dynamics model with a computational model of driver behavior. This model of driver behavior aims to simulate the driver's perceptual, cognitive, and control processes to generate steering, braking, and throttle vehicle inputs. It was primarily developed based on driver performance data collected during on-road instrumented vehicle driving sessions.

The development of this tool is part of an ongoing effort to increase the ability of traffic engineers and highway designers to provide a safer driving environment for the public.

Michael Trentacoste
Director, Office of Safety Research & Development

Notice

Quality Assurance Statement

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16. Abstract

The Federal Highway Administration is currently developing an integrated set of software tools to improve highway design, the Interactive Highway Safety Design Model (IHSDM). The IHSDM is a suite of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane rural highways. The IHSDM provides highway project planners, designers, and reviewers in State and local departments of transportation and engineering consulting firms with a suite of safety evaluation tools to support these assessments. As currently implemented in the latest public release version, the IHSDM includes the following five components: (1) Policy Review Module, (2) Design Consistency Module, (3) Crash Prediction Module, (4) Traffic Analysis Module, and (5) Intersection Review Module. A sixth module, the Driver Vehicle Module (DVM), is a candidate for future release.

This report provides a complete technical description of the DVM. Specifically, it provides a description of the specification, verification, and calibration/validation of the DVM for the passenger vehicle and the heavy vehicle component, along with additional functionality enhancements.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS AND SYMBOLS

CR .... county route
DCM .... Design Consistency Module
DOT .... department of transportation
DVM .... Driver Vehicle Module
FHWA.. Federal Highway Administration
GPS .... Global Positioning System
IHSDM.. Interactive Highway Safety Design Model
MOE.. measure of effectiveness
PC.. point of curvature
PDF .... power density function
PT.. point of tangency
sd .... standard deviation
SD .... sight distance
SR... state route
STI.. Systems Technology, Inc.
URA .... user requirements analysis
VDANL.. vehicle dynamics analysis, non linear
VDM .... Vehicle Dynamics Model
VPI .... vertical point of intersection
VRTC.. Vehicle Research Test Center
VTTI .... Virginia Tech Transportation Institute

SECTION 1. INTRODUCTION

BACKGROUND

The Federal Highway Administration (FHWA) is currently developing an integrated set of software tools to improve highway design, the Interactive Highway Safety Design Model (IHSDM). The IHSDM is a suite of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane rural highways. The IHSDM provides highway project planners, designers, and reviewers in State and local departments of transportation (DOTs) and engineering consulting firms with a suite of safety evaluation tools to support these assessments. As currently implemented in the latest public release version, the IHSDM includes the following five components: (1) Policy Review Module, (2) Design Consistency Module (DCM), (3) Crash Prediction Module, (4) Traffic Analysis Module, and (5) Intersection Review Module. A sixth module, the Driver Vehicle Module (DVM), is a candidate for future release.

The objective of the DVM is to permit the user to evaluate how a driver would operate a vehicle (e.g., passenger car or tractor-trailer) through a geometric design and to identify whether conditions exist that could result in loss of vehicle control (e.g., skidding or rollover). To provide this capability, the module consists of a Driver Performance Model linked to a Vehicle Dynamics Model (VDM), along with other model components needed to provide the necessary information databases. The prototype DVM, which is a time-based simulation model, estimates the vehicle’s speed and path along a two-lane rural highway in the absence of other traffic.

During the course of the DVM development project, the DVM development team has engaged in a series of activities, including:

- Developing initial specifications for the DVM.
- Working with the IHSDM software developer to implement the initial specifications.
- Verifying iterative versions of the DVM.
- Calibrating and validating the DVM.
- Testing the DVM using real-world roadway design scenarios.
- Interactively enhancing the DVM and working with the IHSDM software developer to implement fixes and improvements.

PURPOSE AND ORGANIZATION OF THIS REPORT

This report provides a complete technical description of the DVM. Specifically, it provides a description of the specification, verification, and calibration/validation of the DVM for the passenger vehicle and the heavy vehicle component, along with additional functionality enhancements.

The report is organized as follows:

- Section 2. Description and Development of the DVM.
- Section 3. Specification of the DVM.
- Section 4. Verification, Calibration, and Validation of the DVM.
- Section 5. Summary and Conclusions.

SECTION 2. DESCRIPTION AND DEVELOPMENT OF THE DVM

INTRODUCTION

This section describes the DVM design and development that has taken place throughout the course of the project. An overview of the five major functional components is also provided.

PURPOSE AND STRUCTURE

Figure 1 outlines the information flow within the DVM. The Roadway Geometrics and Driver Geometrics components perform coordinate transformations of the roadway data and compute certain error variables (e.g., vehicle drift rate) that are to be corrected by the driver. The VDM responds to the driver's control input as well as to the gravitational inputs dictated by the roadway geometry to simulate the motion of the vehicle.

The purpose of the driver portion of the DVM is to simulate the driver's perceptual, cognitive, and control processes to generate steering, braking, and acceleration inputs. This module has five major functional components: (1) Perception, (2) Speed Decision, (3) Path Decision, (4) Speed Control, and (5) Path Control. These components are described below.

- **Perception**: This component translates the physical description of the situation contained in the driver input database into estimates of vehicle states, roadway characteristics, and other relevant variables needed by the decision and control modules. These estimates are degraded as a result of driver information-processing limitations.
- **Speed Decision**: This component computes the driver's desired speed profiles. The desired speed profile typically varies during the course of a simulation run and, at any instant, the driver attempts to perform one of the following tasks: (1) maintain a constant speed, (2) generate a deceleration or acceleration profile appropriate to entering or exiting a curve, (3) decelerate because of a condition such as a reduction in posted speed or a stop sign that requires reducing speed or coming to a full stop, or (4) accelerate to resume speed after the slow or stop requirement is no longer relevant. Speed decision may be influenced by limited sight distance (SD) as described elsewhere in this document.
- **Path Decision**: This component computes the desired path profile, which is either the center of the lane for the entire roadway, or—at the option of the user—lane center on tangent sections and a path that optimally "cuts the curve" on horizontal curves.
- **Speed and Path Control**: These components perform the closed-loop tracking tasks of regulating speed and path about the profiles produced by the high-level decision module. Because lateral deviation generally requires substantially tighter control than speed deviation in the absence of traffic, separate model elements for the two regulation tasks are specified to facilitate different modeling approaches and to allow independent development for speed and path control models in the future.

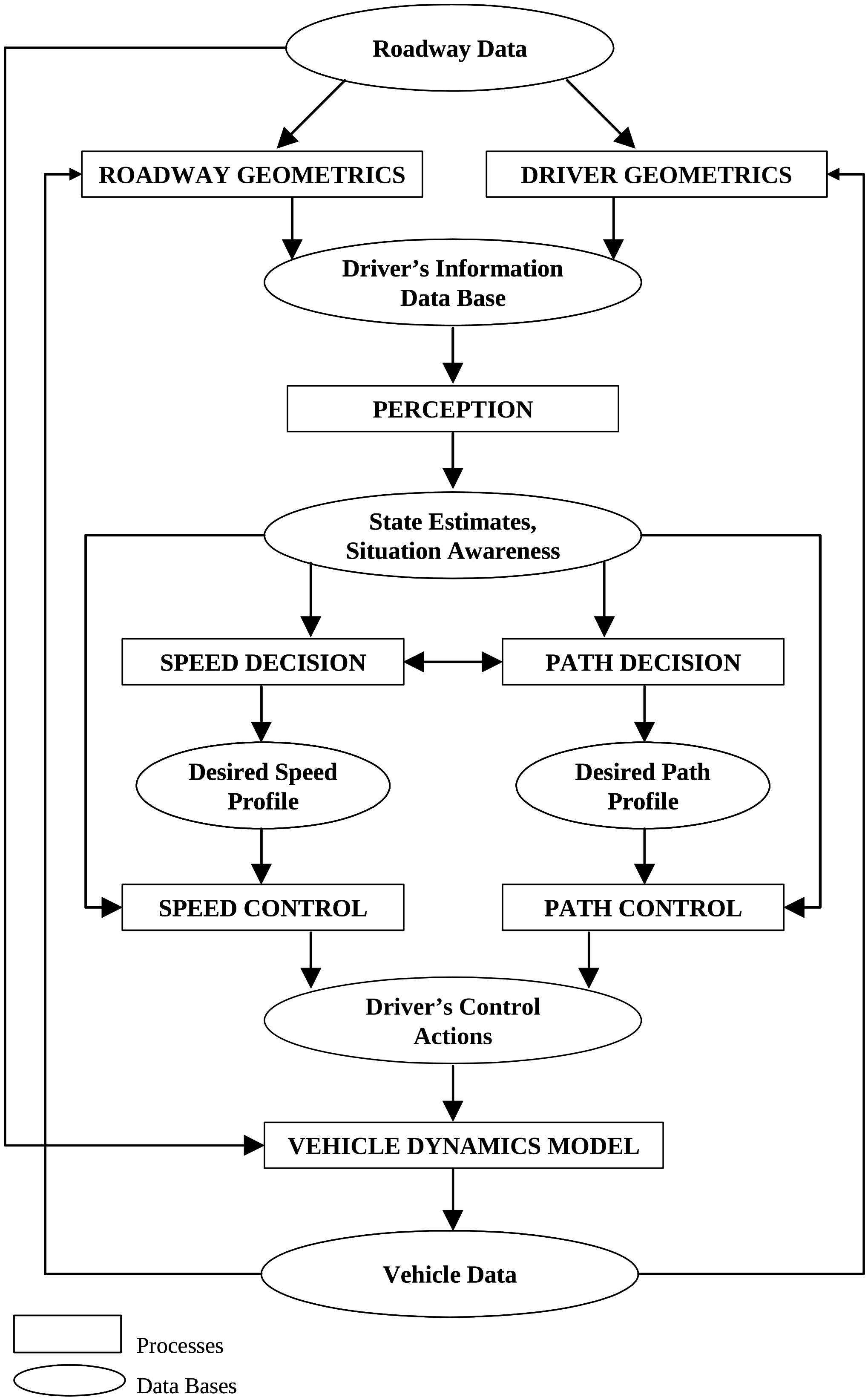


Figure 1. Information flow in the Driver Vehicle Model.

SECTION 3. SPECIFICATION OF THE DVM

INTRODUCTION

This section provides a systematic delineation of the DVM components. Each of the major DVM components are discussed in terms of purpose, assumptions and limitations, computations, and additional specifications, as defined here:

- **Purpose:** A short summary of the role of this component in the DVM.
- **Assumptions and Limitations:** The key assumptions and/or limitations underlying each section of the model are stated explicitly. Assumptions concerning driver behavior that are supported by experimental data are noted. Otherwise, the assumption is based upon the opinion of the development team.
- **Computations:** The important computations performed by each model element are reviewed.
- **Additional Specifications:** The additional enhancements relevant to the component that are necessary for calibration/validation or enhancements that are necessary to improve model performance or address problems are included.

COMPONENTS OF THE MODULE

Roadway Geometry

Purpose

The purpose of the DVM Roadway Geometry component is to interface the DVM with the standard IHSDM roadway model. The standard IHSDM roadway model describes the alignment, cross section, roadside, and ancillary data (e.g. crash data) used by all IHSDM modules. The data used by the DVM include the roadway alignments (horizontal and vertical) and cross slope data.

The IHSDM roadway model consists of data elements that define specific types of data. All data elements have one or more attributes. The model is represented in a three-dimensional space. All elements are tied to the horizontal alignment using one or more station numbers. By definition, station numbers are defined on the centerline of the horizontal alignment, which is extended to XY coordinates. The vertical alignment provides the data to map the horizontal alignment to XYZ coordinates. Table 1 lists the major roadway model data elements that are used by the DVM Roadway Geometry component.

Assumptions and Limitations

The driver model does not recognize horizontal deflections (points where horizontal or vertical alignments have a discontinuity) and will not respond properly if the highway contains such elements. A deflection can be approximated by a very sharp curve. (Note that the DVM is not intended to handle turning at intersections.)

Table 1. Major roadway model elements used by the roadway geometrics component.

Category	Data Element	Attributes
General	Posted speed (if relevant)	Start station, end station, side of road, speed limit
Horizontal alignment	Horizontal tangent	Start station, end station
	Simple curve	Start station, end station, radius, direction of turn
	Spiral curve	Start station, end station, radius, direction of turn, radius position
Vertical alignment	Vertical point of intersection	Vertical point of intersection station, back grade, back length, forward grade, forward length
Cross section	Normal cross slope	Start station, end station, side of road, cross slope
	Superelevation	Superelevation transition-critical stations, full superelevation slope
	Sight distance obstruction offset	Start station, end station, obstruction offset from centerline
	Shoulder width	Start station, end station, shoulder width
Lane	Thru lane	Start station, end station, side of road, width
	Auxiliary lane	Start station, end station, side of road, width, begin full width, end full width, is passing prohibited in opposing lanes?
	Offset	Start station, end station, side of road, full offset, begin fill width, end full width
	Widening	Start station, end station, widening, begin full width, end full width

The vertical alignment must be defined so the back grade of a vertical point of intersection (VPI) element is equal to the forward grade of the previous VPI element.

Computations

Most calculations in the Roadway Geometry component are simple coordinate transforms. The only exception to this is the calculations used to compute the available SD. The SD calculation is composed of a two-dimensional calculation for the vertical alignment and a two-dimensional calculation for the horizontal alignment. The horizontal alignment SD calculation assumes an infinitely tall SD obstruction at the outer edge of each shoulder or the edge of the pavement if there is no shoulder. The default assumption may be modified using the Sight Distance Obstruction Offset data element.

The available SD calculation starts from the driver position. The driver's eye height is assumed to be 1070 mm, and the object height is 150 mm. These values are not modifiable by the user.

The available SD is first calculated for vertical alignment. This calculation uses the vertical elevation and cross slope to determine if any point obstructs the line of sight in the vertical alignment. The algorithm then calculates the available SD using the horizontal alignment and obstruction offset (either shoulder edge or SD obstruction offset). At the user's option, the available SD is either the minimum of the available SD in the vertical plane and horizontal plane, or only the limitation imposed by the vertical alignment.

If the scenario contains no significant horizontal sight limitations, the user should specify vertical-only sight-distance limitations to avoid the automatic imposition of an assumed wall located at the edge of the shoulder.

Driver Geometrics

Purpose

The Driver Geometrics component computes drift (rate of change of path error), heading error, and yaw rate (turn rate) error for use by the driver for determining steering response. Path error—defined as the location of the vehicle relative to lane center—is computed by the VDM.

Assumptions and Limitations

The algorithms underlying the driver model assume that errors are sufficiently small to justify linear-systems analysis (e.g., that the sine of the heading error is very close to the value of the heading error in radians). For a standard two-lane highway, this condition will be met if the vehicle stays on the paved surface.

At the option of the user, the simulation will be terminated if all four tires of a passenger car or all tires of a truck tractor leave the paved surface. The IHSDM evaluation report will not be available if the simulation is terminated in this manner, but the optional file of time-history data will contain results up to the time of termination. If the user does not choose this option the simulation will run to completion even if the vehicle leaves the paved surface, in which case the validity of the predicted driver/vehicle behavior may be compromised

Computations

The yaw rate error is defined as the difference between the yaw rate of the vehicle and the effective yaw rate of the road, which is computed as the speed of the vehicle in m/s multiplied by the curvature of the road in radians/meter. To provide sufficient preview to allow the driver to start turning the steering wheel before curve entry is reached, the curvature of the road one time constant ahead (typically, the distance traveled in roughly 1 second) is used in this calculation.

The heading error is computed as the difference between the vehicle's direction of travel and the local heading of the road.

Drift is computed by effectively differentiating the path error. Thus,

$$D[k] = (Y[k] - Y[k\text{-}1]) / \Delta T \qquad (1)$$

where

$D[k]$ is the drift computed at the current simulation time index,

$Y[k]$ and $Y[k\text{-}1]$ are the path errors computed for the current and previous indices, respectively, and

ΔT is the time step interval.

Values of these variables computed for a given time step are used by the perception module for the next time step.

Perception

Purpose

The perception module translates the physical description of the driving environment into estimates of vehicle states, roadway characteristics, and other relevant variables needed by the decision and control modules. At the user's option, this component provides the decision and control modules with estimates of perceptual variables, relevant to the driving task, that are perturbed by a random disturbance (noise) and/or exhibit a consistent error (bias). The imposition of perceptual noise allows the DVM to treat errors in perceiving and reacting to informational quantities relevant to the driving task, and it provides a mechanism for inducing response variability within and across trials. Perceptual variables are enumerated in the section on Computations below.

Assumptions and Limitations

Five assumptions underlie computations in the perceptual module:

- **The driver's perceptual process provides the driver with noisy estimates of relevant perceptual variables.** This assumption is supported by both psychophysical data and by the results of experiments in manual control. The psychophysical data support the notion of perceptual thresholds, or just-noticeable differences, that characterize the uncertainty and variability in judging whether or not a signal is different from zero or other target value. Manual control data, obtained mostly in laboratory settings under constrained conditions, show that a substantial portion of the human's response behavior is related to variability within the human's information-processing system. For mathematical convenience, this response variability is generally modeled as a random noise process associated with perception.
- **The driver estimates the speed appropriate to an upcoming curve based on past experience in traversing similar curved segments.** This is an opinion of the authors. In terms of the algorithm specified for the model, the consequences of this assumption are identical to an alternative assumption that the driver estimates the curvature and computes the desired speed based on this estimate.
- **The driver effectively flattens the curve by beginning the turning maneuver before curve entry and by beginning the straightening-out maneuver before curve exit.** Simulator and on-road data support the hypothesis that some drivers adopt this strategy. As noted above, the user has the option to explore this strategy or to explore the hypothesis that drivers always attempt to remain in the center of the lane.
- **The error associated with estimating horizontal curvature decreases in proportion to the distance from curve entry.** This reflects a broad underlying assumption, supported by psychophysical experimentation, that the ability to resolve a signal improves in direct proportion to increases in its magnitude. The size of the retinal image of the roadway in the vicinity of the upcoming curve varies inversely with distance to the curve.

- **The driver uses the rate of expansion of the optical target image to determine appropriate deceleration for stopping**. Experimental data have been reported that are consistent with this hypothesis that drivers use variables based on rate of optical expansion in their braking.

Computations

Estimates of the following state variables are computed:

- Longitudinal acceleration.
- Lateral acceleration.
- Yaw (turning) acceleration.
- Yaw rate error, defined as the difference between vehicle yaw rate and the effective roadway yaw rate (i.e., velocity times curvature). In order for the driver to anticipate a curve, yaw rate error is computed from the road curvature one preview distance ahead. The preview distance is computed as the velocity times the time constant computed in the path-control module for yaw-rate control.
- Rate of change of the optical target image at a stopping location. This information is used to generate an appropriate braking strategy.
- Vehicle velocity.
- Distance to a curve entry or stopping point.
- Deviation of vehicle position from lane center (path error).
- Rate of change of lane position (drift).
- Appropriate negotiation speeds for the curves ahead.

Whenever the driver updates the estimate of a particular variable, the new estimate consists of the true simulated variable potentially corrupted by both a bias factor and additive zero-mean Gaussian noise. The bias factor is intended to account for a consistent over- or underestimation of the variable, e.g., a tendency to underestimate vehicle speed. For example, a bias of 0.9 represents a 10 percent underestimation of the magnitude of the variable, 1.1 represents a 10 percent overestimation, and 1.0 represents the lack of a consistent directional error.

Potential sources of estimation bias include underestimation of vehicle velocity as perceived from the visual flow field by driver used to a lower-profile vehicle having a lower eye height, or the misestimation of the horizontal curvature ahead when the curve and approach tangents are on different grades. We are not aware of data to support specific numeric values for nonunity bias factors, however.

In general, a Gaussian random noise process is added to the perceived variable to account for both the effects of perceptual resolution limitations (e.g., thresholds) and for uncertainties that tend to scale with the magnitude of the variable, which are accommodated in the DVM by noise scale factors. Noise processes are modeled as a Gaussian white noise shaped by a first-order filter that limits rates at which instantaneous estimation errors can change over time.

Figure 2 is a flow diagram of the computational procedure. The algorithms for performing the computations are as follows:

Consider the generic variable *x* that is to be estimated by the driver. Computation of its perceptual estimate involves the following parameters that are assumed constant for the duration of the model run:

T	simulation time step (seconds),
x_tc	time constant for the noise filter associated with *x* (seconds),
x_bias	bias factor for estimating *x* (dimensionless),
x_thresh	perceptual threshold for *x* as a noise standard deviation (units of *x*), and
x_sf	scale factor associated with noise component that scales with *x* (dimensionless).

Also computed in the course of these is the constant:

x_decay	filter decay factor associated with estimation error (dimensionless)

where

$$x\_decay = \exp(-T/x\_tc). \quad (2)$$

Finally, the following are recomputed at every time step:

$$\sigma = \{[x\_thres^2 + (x\_sf * x(k))^2]/T\}^{1/2} \quad (3)$$

$$n = \sigma * \nu(k+1) \quad (4)$$

$$x\_err(k+1) = x\_decay * x\_err(k) + (1.0 - x\_decay) * n \quad (5)$$

$$x\_est(k+1) = x\_bias * x(k) + x\_err(k+1) \quad (6)$$

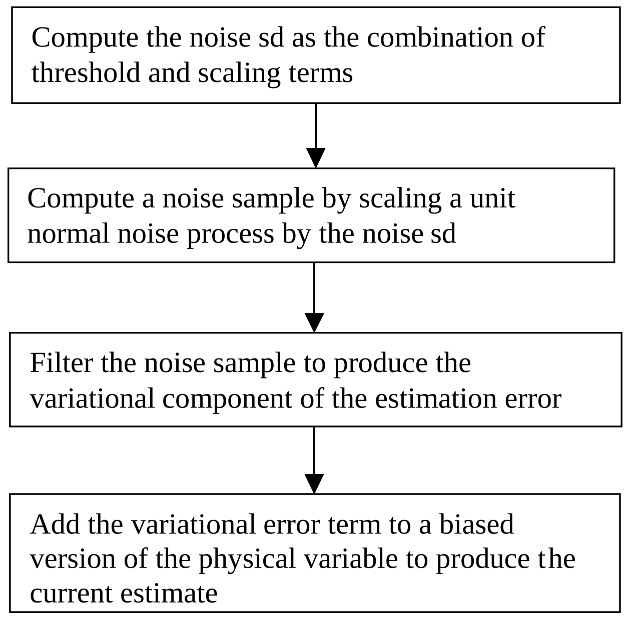
where

k	sample index, where each increment corresponds to an advance of *T* seconds,
x	physical variable of interest,
x_est	driver's estimate of *x*,
x_err	noise-related estimation error associated with *x*,
n	unfiltered noise sample,
σ	instantaneous standard deviation associated with *n*, and
ν	sample from a unit normal distribution.

Because the driver's ability to estimate the appropriate negotiation speed is assumed to increase with decreasing distance to the curve, the corresponding noise scale factor is computed in the DVM as a curve-noise constant multiplied by the distance to the curve.

A random number generator, modified to approximate a normal probability density, is used to produce each noise sample required by the DVM. Trial-to-trial response variability is obtained by initiating the random number generator with different seeds on successive model runs.

Specifying independent values of filter time constant, bias, threshold, and noise scale factor for every perceptual variable used by the driver would lead to more parameters than experimentally quantifiable. Accordingly, nonzero or otherwise off-nominal values for such variables are selected only where they are expected to materially influence model predictions.



sd = Standard deviation

Figure 2. Flow diagram of the computation of perceptual estimates.

The following approach to selecting independent driver-related model parameters is based partly on previous studies of human perception and on model sensitivity analysis. It is consistent with the DVM's primary goal of exploring the effects of highway geometry on speed behavior.

- A single time constant for noise filtering, set at 2 seconds, is applied to all noise processes.
- Noise scale factors, thresholds, and biases are adjusted independently for estimation of current vehicle velocity and for curve negotiation velocity. The scale factors and thresholds have been determined on the basis of realistic driving tasks and/or laboratory psychophysical experiments. The bias terms may be determined from new or published data or may serve as user-adjusted independent parameters of the model analysis.
- A single generic noise scale factor is assigned to all lateral-axis perceptual variables and with longitudinal acceleration. Lateral-axis variables are path error, drift, yaw-rate error, and yaw acceleration.
- Thresholds associated with perception of path error and yaw-rate error are kept as independent parameters and adjusted on the basis of new or published performance data only when more accurate predictions of lateral-axis behavior are desired.
- Thresholds are ignored and bias terms are set to 1.0 in the default driver configurations.

Path Decision

Purpose

The Path Decision component computes the desired track to be followed by the Path Control component.

Assumptions and Limitations

One of two possible assumed strategies is followed as determined by the driver type selected by the user:

- Driver attempts to maintain lane center over the entire roadway.
- Driver attempts to cut the curve; i.e., follow a curved path that is flatter than the path defined by the lane center, in the vicinity of a horizontal curve. Otherwise, the driver attempts to track lane center.

Computations

An exaggerated diagram of curve cutting is illustrated in figure 3. The actual path of the highway, geometric curve, is indicated by the solid line; whereas the virtual curve path assumed to be followed by the driver is dashed. The virtual curve is a circular arc having the largest radius that begins and ends on lane center, is tangent to the lane edge at these locations, and achieves maximum allowable deviation from the geometric lane center at the midpoint of the geometric curve. The entry points of the geometric and virtual curves are respectively denoted by S_{ce} and S_{cev}.

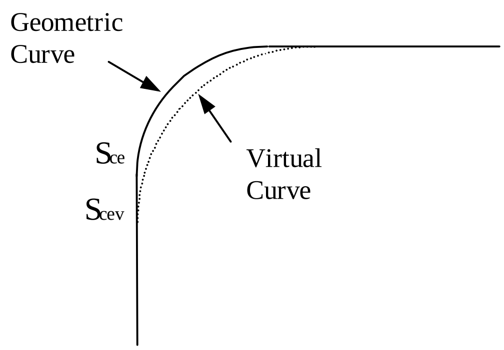


Figure 3. Diagram of the assumed path through a horizontal curve.

The virtual radius of curvature R_v and virtual curve entry location S_{cev} may be easily derived under simplifying assumptions. Equations 7 and 8 respectively define:

$$R_v = R + Y_{max} \cos(\theta/2)/(1 - \cos(\theta/2)) \quad (7)$$

and

$$S_{cev} = S_{ce} - Y_{max} \sin(\theta/2)/(1 - \cos(\theta/2)) \quad (8)$$

under assumptions of a simple curve of radius *R*, total deflection angle (i.e., arc length) θ, and maximum allowable deviation from center of Y_{max}. (Y_{max} is computed as half of the difference between lane width and vehicle width minus the lane margin—a driver parameter reflecting the allowable distance of the vehicle (tractor), e.g., from the lane edge). Note that c*hanges* in curve radius and entry depend only on the total curve deflection and maximum lane deviation and not on the geometric radius. If the calculated value for Y_{max} becomes negative, the DVM terminates with an appropriate end message.

In order for the driver model to exhibit the desired curve-cutting behavior, it is necessary to approximate the path defined above by an analytic expression for which path, drift, and curvature are self-consistent. The following combination of second- and third-order polynomials has been found to provide the desired approximation:

- A second-order polynomial extending from the entry station of the virtual curve to the entry station of the geometric curve.

  Parameters are selected such that the curvature of this parabolic segment is approximately that of the curvature of the virtual curve.
- A third-order polynomial from the entry of the geometric curve to the midpoint of the curve.

  Parameters are selected such that (a) the displacement and slope of this segment matches that of the parabolic segment at the point of geometric curve entry, (b) the curve attains maximum desired displacement at the curve midpoint, and (c) the curve has zero slope at the curve midpoint. Slope is defined here as the derivative of the path deviation with respect to station.
- A third-order curve that is the mirror image of the foregoing, reflected about the curve midpoint, extending from curve midpoint to the exit station of the geometric curve.
- A parabolic segment that is the mirror image of the initial parabolic segment from the exit station of the geometric curve to the exit station of the virtual curve.

The algorithm for forcing the driver to cut the corner consists of two parts: (1) a set of computations that is completed once per curve, and (2) additional computations that are performed every simulation update.

Computations Once Per Curve

The computations given here are performed the first time a horizontal curve becomes relevant and are not performed again until another curve becomes relevant. A curve becomes relevant when it is the next curve ahead once the driver has finished negotiating a curve. The initial curve of the roadway is relevant when the simulation starts. (If the driver is assumed to cut corners, the simulation should begin on a tangent sufficiently ahead of the first curve so that the driver is not immediately turning.)

The following variables serve as inputs to the algorithm:

sce	location (station) of the geometric curve entry (m),
scev	location of the virtual curve entry (m),
scx	location of the geometric curve exit (m),
scxv	location of the virtual curve exit (m),

r	geometric curve radius (m) (always positive),
ymax	maximum deviation from lane center (m) (always positive), and
sgn	1.0 for right curve, -1.0 for left curve.

The following computations are performed once per curve:

$$scxv = sce + scx - scev \quad (9)$$

$$smid = (sce + scx)/2.0 \quad (10)$$

$$r2 = r*r \quad (11)$$

$$cv0 = 1.0/rv \quad (12)$$

$$a0 = 0.5*cv0 \quad (13)$$

$$dtemp = sce - scev \quad (14)$$

$$y1 = a0*dtemp*dtemp \quad (15)$$

$$dydx1 = cv0*dtemp \quad (16)$$

$$dtemp = smid - sce \quad (17)$$

$$b1 = (3.0*ymax - 3.0*y1 - 2.0*dydx1*dtemp)/(dtemp*dtemp) \quad (18)$$

$$b2 = 2.0*b1 \quad (19)$$

$$c1 = (-2.0*ymax + 2.0*y1 + dydx1*dtemp)/(dtemp*dtemp*dtemp) \quad (20)$$

$$c3 = 3.0*c1 \quad (21)$$

$$c6 = 6.0*c1 \quad (22)$$

All of these computed variables, with the exception of *dtemp*, are needed for the updates performed at every simulation interval.

Computations Performed Every Simulation Interval

In addition to the inputs and computed variables listed above, the following variables serve as inputs to the algorithm executed every time step:

prev	preview (look-ahead) distance, (m)
s	current station (m)
v	current velocity (m/s)
c	curvature of the geometric road at the preview distance (rad/m) (positive for right curve, negative for left)

Note that *c* is the instantaneous curvature at the preview distance, which is zero if on the tangent, 1/*r* (with proper sign) if on the geometric curve, and something in between if on a spiral segment.

The following are the primary outputs of this algorithm:

ycorr	correction to path error (m),

dcorr correction to drift (m/s), and

yrcorr correction to yaw rate error (rad/sec).

These variables are used to correct the driver's estimates so that the driver attempts to minimize deviations about these desired values rather than about zero. For example:

$$y\text{-}estimate\text{-}corrected = y\text{-}estimate - ycorr \tag{23}$$

where

y-estimate-corrected estimated path error operated on by the driver, and

y-estimate estimated deviation of lane position from lane center.

The computations described in figure 4 are performed every simulation interval:

```
// Compute ycorr & dcorr for station s
  {if (s <= scev)
    {ycorr = 0.0;
     dydx = 0.0;
    }

    else if (s <= sce)
    {delx = s - scev;
     ycorr = a0*delx*delx;
     dydx = cv0*delx;
    }

    else if (s <= smid)
    {delx = s - sce;
     delx2 = delx*delx;
     delx3 = delx2*delx;
     ycorr = y1 + dydx1*delx + b1*delx2 + c1*delx3;
     dydx = dydx1 + b2*delx + c3*delx2;
    }

    else if (s <= scx)
    {delx = scx - s;
     delx2 = delx*delx;
     delx3 = delx2*delx;
     ycorr = y1 + dydx1*delx + b1*delx2 + c1*delx3;
     dydx = -dydx1 - b2*delx - c3*delx2;
    }

    else if (s < scxv)
    {delx = scxv - s;
     ycorr = a0*delx*delx;
     dydx = -cv0*delx;
    }

    else
    {ycorr = 0.0;
     dydx = 0.0;
    }

// Compute cv for station sprev
    sprev = s + prev;
    if (sprev <= scev)   cv = 0.0;

    else if (sprev <= sce)  cv = cv0;

    else if (sprev <= smid)
    {delx = sprev - sce;
     delx2 = delx*delx;
     delx3 = delx2*delx;
     ycorr1 = y1 + dydx1*delx + b1*delx2 + c1*delx3;
     dydx2 = b2 + c6*delx;
     l1 = r - ycorr1;
     cv = 1.0/l1 + r2*dydx2/(l1*l1);
    }

    else if (sprev <= scx)
    {delx = scx - sprev;
     delx2 = delx*delx;
     delx3 = delx2*delx;
     ycorr1 = y1 + dydx1*delx + b1*delx2 + c1*delx3;
     dydx2 = b2 + c6*delx;
     l1 = r - ycorr1;
     cv = 1.0/l1 + r2*dydx2/(l1*l1);
    }

    else if (sprev < scxv)  cv = cv0;

    else  cv = 0.0;

// Compute outputs
    ycorr = sgn*ycorr;
    dcorr = sgn*v*dydx;
    yrcorr = v*(sgn*cv - c);
```

Figure 4. Pseudo-code for calculating path decision.

Path Control

Purpose

The Path Control component generates wheel movements to regulate lateral placement (path) by following commands generated by the path decision component.

Assumptions and Limitations

- The driver mentally constructs a linear model of the path-regulation task which includes a second-order model of vehicle yaw response.

  Data obtained from simulator and on-road studies of driving behavior were consistent with the hypothesis that the driver constructs an adequate mental model of system dynamics. Analysis of the VDM supports a second-order linear approximation to yaw rate response.
- The driver adopts a linear response strategy to control heading and lateral path.

  A considerable body of literature supports the assumption that linear models provide good replications of human operator response strategies in many situations where the system to be controlled can be adequately represented as a linearly responding system. Our on-road research results also were consistent with this linear assumption.

Computations

A linear strategy is employed using a successive loop-closure technique described below, with the exception that an acceptable tolerance may be specified below which the driver does not attempt to reduce path error. (The tolerance is zero in the default driver configurations provided in the IHSDM.)

This strategy subdivides the control task into a series of subtasks, where, at each step, the system to be controlled is approximated by the combination of an effective time delay τ, an integration, and a scale factor K_v. Such a system can be well controlled with a simple feedback gain of:

$$K_c = -\pi/(2\ \tau\ K_v\ G_m) \quad (24)$$

where

the minus sign provides the necessary negative feedback to reduce system errors,

G_m is the gain margin constant,

τ is in seconds,

the units of K_v depend on the variable being controlled and the effective control input,

K_c has units that are the reciprocal of $\tau\ K_v$, and

G_m is dimensionless.

Theoretically, the minimum G_m value is 1.0, which represents a controlled system on the verge of instability. Increasing values of G_m provide increasing margins of stability at a cost of increasingly sluggish response. For this driver model, a gain margin of about 3.0 was found to provide a relatively rapid response with little oscillatory behavior.

Figure 5 diagrams an approximation to the task of regulating vehicle lane position, which is modeled as a succession of three subtasks: regulation of yaw-rate error, drift, and path error. Sufficiently small values are assumed for the angle between the vehicle velocity vector and local tangent to the road, the drift rate, and path deviation from lane center such that the sine of any angle variable appearing in the calculations may be replaced by the value of the angle in radians, and its cosine may approximated as unity.

The driver's primary input is considered to be a commanded rate of change of the steering wheel angle. A single integration yields wheel angle, which is related to yaw rate (vehicle rate of turn) by the vehicle dynamics. The yaw-rate error is defined as the difference between the vehicle turn rate (more precisely, rate of vehicle velocity vector rotation) and the effective roadway turn rate (i.e., vehicle velocity times local road curvature). Integration of yaw-rate error yields heading error, i.e., difference between velocity vector and local road tangent. Heading error multiplied by velocity yields a close approximation to drift. Integration of drift subsequently yields path error. The approximation to the steering task shown above is used only for determining the driver's control strategy. Actual vehicle response dynamics are simulated to a high degree of fidelity in the VDM component of the DVM.

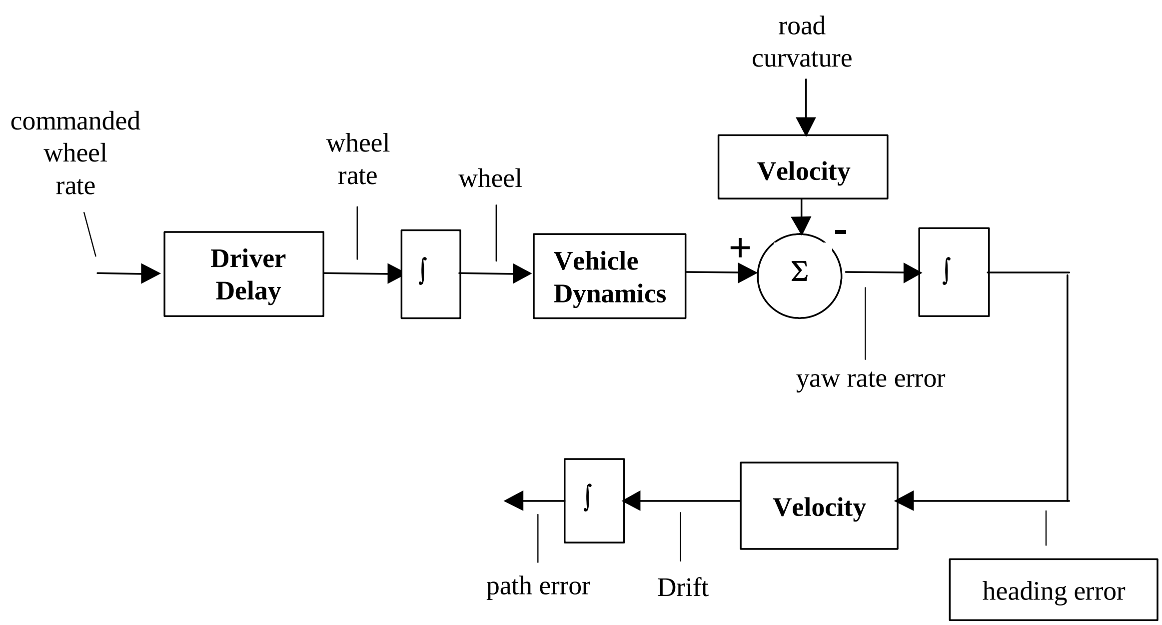


Figure 5. Flow diagram of an approximation to the path-regulation task.

For the purpose of computing control gains, vehicle steering dynamics are represented by a second-order filter having a steady state gain K_v relating yaw-rate to steering wheel angle and a natural frequency of ω_o. Because these parameters are speed dependent, the path control module contains a table of K_v and ω_o obtained from the yaw-rate response of the VDM at selected speeds. Interpolation of model table entries is performed at each simulation iteration to determine the instantaneous values of K_v and ω_o.

Computation of driver control gains is performed inside out; i.e., the gain related to yaw rate regulation is computed first, then the gain related to drift regulation, and finally the gain related to path regulation. The phase shift of this filter is approximated by an equivalent delay of $0.7/\omega_o$. To compute the gain on yaw-rate error, the driver delay τ_d is combined with the equivalent vehicle delay to yield an effective delay:

$$\tau_e = \tau_d + 0.7/\omega_o \tag{25}$$

which with application of equation 24 yields the feedback gain K_r on yaw rate error:

$$K_r = -F/(K_v\ \tau_e) \tag{26}$$

where

$$F = \pi/(2\ G_m) \tag{27}$$

The inner-loop control task of regulating yaw rate is now approximated by a new effective delay of $(0.7\ \tau_e)/F$, where the factor 0.7 matches the phase lags of the yaw-rate control loop and the effective pure delay at about –50 degrees.

The feedback gain on drift is computed by considering the task of controlling drift with a yaw-rate command, where the effective controlled element is now the effective delay mentioned above, plus an integration scaled by velocity. Application of equation 24 to this control task yields the following feedback gain K_d on drift:

$$K_d = -F^2/(0.7\ \tau_e\ V) \tag{28}$$

Carrying this process one more step yields the following feedback control gain K_y on path error:

$$K_y = -F^3/(0.7^2\ \tau_e) \tag{29}$$

To represent the driver's tolerance of small path errors, the feedback term K_y is set to zero whenever the magnitude of the path error is less than a user-specified tolerance. For improved response, an additional feedback gain of K_r/ω_o is applied to yaw acceleration.

To determine the control strategy, the above gains are applied in an outside-in manner. The gain K_y is applied to path error to generate a drift command. The difference between the instantaneous drift and the commanded drift is scaled by the gain K_d to generate a yaw rate command. The commanded wheel rate is computed by adding two terms: (a) the gain K_r acting on the difference between the instantaneous and commanded yaw rates and (b) the gain on yaw acceleration acting on yaw acceleration.

The steering control laws are thus generated in a relatively straightforward manner on the basis of vehicle response parameters and two driver-related parameters: (a) time delay, which is assumed to relate to inherent information-processing capability, and (b) the gain margin, which is assumed to be largely under the driver's control and is considered an aspect of driver preference or driving style.

Speed Decision

Purpose

The speed decision module generates speed or acceleration commands to be acted upon by the speed control module.

Assumptions and Limitations

It is assumed that the driver:

- Attempts to maintain a preferred free speed (V_{free}) when not limited by highway geometry, posted speed limits, stop signs, or other vehicles. (Other vehicles are not considered in this implementation.)
- Prefers to decelerate at a relatively low constant (preferred) deceleration Ax_{nom}. If necessary, a larger (maximum) deceleration not exceeding Ax_{max} will be commanded.
- Estimates the appropriate speed for negotiating a curve ahead on the bases of past experience with curves in general.
- Attempts to negotiate a horizontal curve with a lateral acceleration that varies as the square root of the curvature.

Computations

Each time the speed decision module is entered, the situation is analyzed to determine whether the driver needs to decelerate or accelerate. Factors requiring deceleration are:

1. Going faster than desired in a curve.
2. A traffic control device ahead requiring a full stop.
3. A speed advisory for the driver to slow down.
4. A curve ahead that requires the driver to slow down.

If any of these factors requires a deceleration greater than some threshold value, a deceleration is commanded which, if held constant, is expected to bring the car to a stop or to the desired reduced speed as the target is reached. If no deceleration is required, and the vehicle is proceeding at less than the currently desired speed, a command to maintain the currently desired speed is generated.

Prior to the start of the simulation, the DVM computes a desired speed V_c and desired lateral acceleration Ay for each horizontal curve as follows:

$$V_c = K\,R^{1/4} \qquad \text{subject to the limitation } V_c \leq V_{free} \tag{30}$$

$$Ay = K^2/R^{1/2} \qquad \text{subject to the limitation} \leq Ay_{max}\ (5) \tag{31}$$

where

K is a constant reflecting vehicle response characteristics as well as driver preferences and is based on both theoretical(1) and empirical(2–4) studies,

Ay_{max} is the maximum tolerable lateral acceleration, and

R is the geometric radius if the driver attempts to maintain lane center or the virtual radius if the driver cuts the curve.

Figure 6 shows the major computational operations of the speed decision module. If the vehicle is negotiating a curve at a speed with excess lateral acceleration, a deceleration of Ax_{max} is commanded. Otherwise, acceleration commands are computed for the following contingencies, where the relevant events are either visible or otherwise known to the driver:

- **Driver is assumed to obey posted speed limits (a parameter set by the user)**, whereby a corresponding acceleration is computed:

$$A_{posted} = (V_p^2 - V^2)/(2.0\ D_p) \tag{32}$$

where

V_p = next posted speed,

V = estimated current vehicle speed, and

D_p = estimated distance to the next speed limit sign.

- **Next posted speed is less than the posted speed currently operative**, whereby a deceleration is computed that would be expected to achieve the next posted speed at the point where indicated (an assumption of the model developers). If the next posted speed limit is higher than the current limit, the acceleration is set to the preferred acceleration.
- **Stop sign ahead**, whereby the following deceleration is computed which, if held constant, brings the vehicle to a stop at the stop sign location:

$$A_{stop} = -(V\ E)/2.0 \tag{33}$$

where

E is the fractional rate of expansion of the retinal image formed by the stop sign (or other object at same distance).

The optical expansion (rad/s) approximation used in the DVM for this psychophysical variable is V/D_s, where D_s is distance to the stop sign.

- **One or more curves ahead**, whereby the following acceleration value is computed which, if held constant, is expected to achieve the desired curve speed at entry:

$$A_{curve}[\mathrm{i}] = (V_c[\mathrm{i}]^2 - V^2)/(2.0\ D_c[\mathrm{i}]) \tag{34}$$

where

V_c = estimated curve negotiation speed as given in equation 30, and

D_c = estimated distance to curve entry.

The largest (negative) acceleration computed for the set of curves is selected as the relevant curve deceleration.

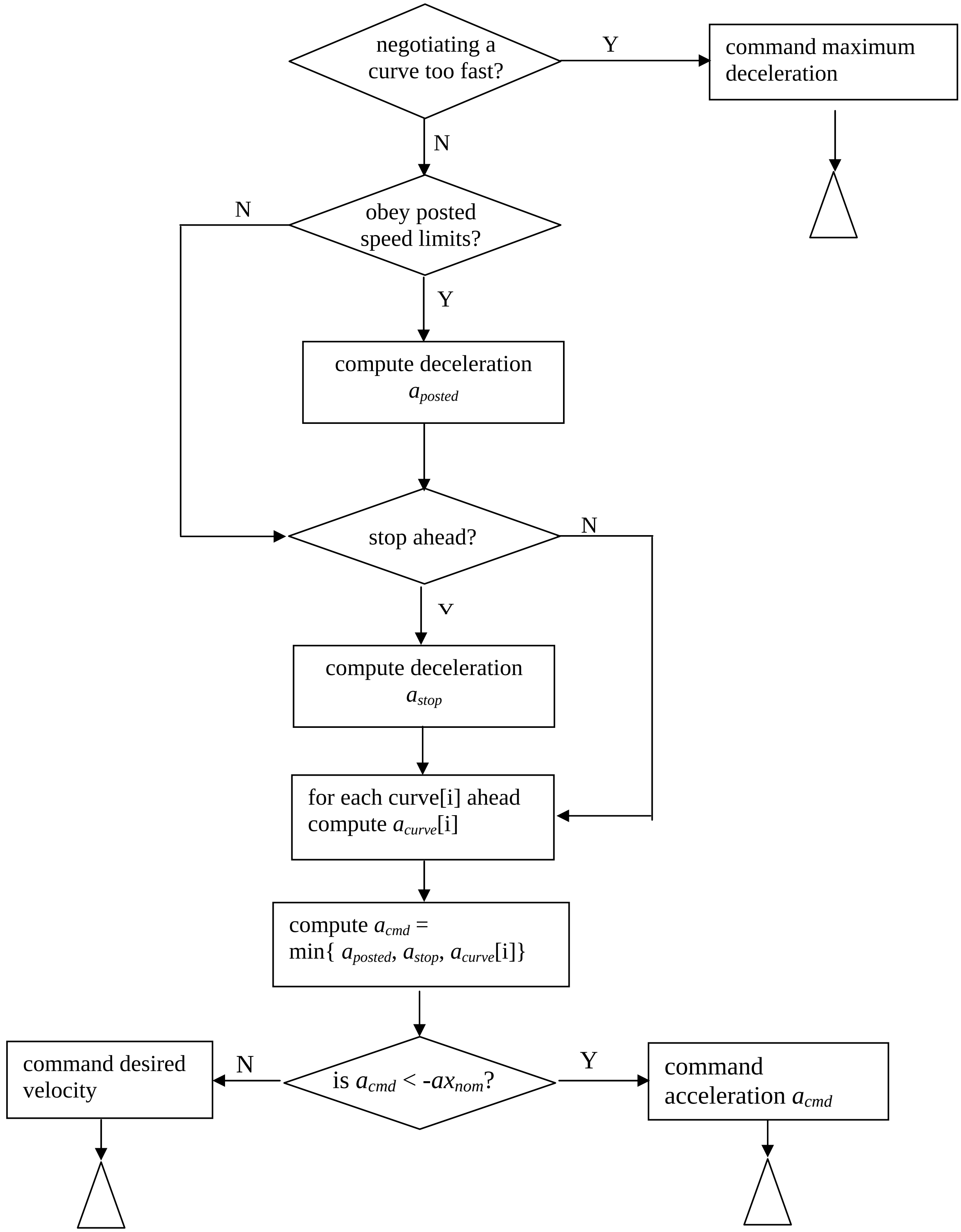


Figure 6. Simplified flow diagram of the speed decision logic.

The DVM selects, from the above alternatives, the largest deceleration (i.e., most negative acceleration) as the tentative acceleration command A_{cmd}. If A_{cmd} is less than $-Ax_{nom}$, it is sent to the speed control module as an acceleration command, subject to the restriction of not being more negative than $-Ax_{max}$. Otherwise, a command is sent to maintain or acquire a velocity that is the minimum of:

- Preferred free speed,
- Current posted speed, if obeying posted speed limit, or
- Appropriate speed for the horizontal curve currently being negotiated.

The speed decision module has additional features. Specifically, if the vehicle has stopped at a stop sign, a counter is set. The decision logic described above is then bypassed until a wait time has passed (user defined). In addition, one of the following treatments is employed for events that are beyond the available SD, depending on the Road Familiarity option set by the user in the IHSDM Administration Tool:

- **The driver is familiar with the road and knows what lies beyond.** In effect, the SD limitation is ignored.
- **The driver assumes a long tangent just beyond the visual range.** In effect, nothing lies beyond visual range requiring driver to slow down.
- **A maximally cautious driver assumes a stopping requirement just beyond visual range.**
- **The driver assumes road geometry beyond the SD is similar to that recently negotiated.** In effect, a horizontal curve of the same geometry as the curve most recently negotiated is assumed.

The long-tangent assumption has been selected for the default driver configurations provided in the IHSDM.

Highway-related factors influencing SD in the DVM are vertical crest and obstruction offsets. The driver model also contains a variable representing the driver's maximum SD. This variable, accessible through the Administration Tool, is set to 1,000 m in the default driver configurations. A lower value could be selected to reflect environmental (e.g., weather) limits to SD.

Additional Specification

More accurately model the relation between acceleration and required speed change:

The DVM assumes that the driver's preferred deceleration or acceleration during curve approach and after curve exit is the same for all horizontal curves. The data, however, are more consistent with the assumption that such accelerations and deceleration vary with the square root of the total desired speed change. A theoretical construct has been defined that predicts the fore-mentioned square-root relationship between the acceleration or deceleration and the desired speed change.[(3)] Existing data obtained in the on-road studies could be used to quantify the parameters of this model.

In order for such a model to be applicable, however, it is necessary to have a model for predicting the desired tangent speeds between two curves. We originally suggested that an optimization algorithm be sought to develop such a model—an effort that we consider to be beyond the scope of the present effort.

At the suggestion of the FHWA, we agreed to explore the approach taken in a previous study.[5] This study was not entirely applicable, however, as it explored only long tangents, defined as tangents where the driver can reach and maintain the desired speed. Furthermore, the authors concluded that their findings "indicated that combinations of alignment indices and other geometric variables were not able to significantly predict the 85th percentile speeds of motorists on long tangents of two-lane rural highways."

Two other studies of speed on two-lane rural highways were reviewed. Figueroa and Tarko[6] developed regression models for predicting mean speed and speed dispersions in curves and on tangent approaches to curves. They developed a 12-factor model for mean speed, but curvature was characterized simply by a binary value (1 if radius greater than 1,700 ft, 0 otherwise), and tangent length and characteristics of preceding curve were not considered.

Polus, Fitzpatrick, and Fambro[1] explored and developed regression models for the effects of preceding and following horizontal curves on the intervening tangent speeds. They concluded that tangent length and radii of preceding and following curves were the most important variables in the regression equations. They also concluded that a single model for tangent speed was inadequate because of the low R^2, and they subsequently developed four models using descriptors of the highway environment based on curve radii and intervening tangent length. While this study is the most relevant of the three studies reviewed here, we have decided not to attempt to implement the results in the DVM for the following reasons:

1. The models are limited to pairs of preceding and following horizontal radii that are either both less than or equal to 250 m, or both greater than 250 m.
2. Insufficient data exist to validate one of the models.
3. The model forms are markedly different from the component models currently used in the DVM, and it is not clear that sufficient resources are available for implementation and testing of these models in the current study.

We suggest that an optimization approach similar to that used in the current DVM be pursued in a subsequent model development effort.

Speed Control

Purpose

The speed control component generates accelerator and brake pedal actions to regulate the speed or acceleration as commanded by the speed decision component.

Assumptions and Limitations

The accelerator and brake are operated by a single foot which is always in one of the three following conditions:

1. Operating the accelerator,
2. Operating the brake, or
3. Transitioning between brake and accelerator.

The driver adopts a linear control strategy to regulate either speed or acceleration.

Computations

The speed control algorithm consists of: (1) a wait period, in which no action is taken, to reflect the time it takes the driver to transition from one pedal to the other; (2) a time delay to reflect delays associated with the driver's perceptual/motor response, and (3) three bounded linear systems. The latter convert a speed-command into an acceleration command, operate the accelerator to achieve the desired acceleration, and operate the brake to achieve the desired (negative) acceleration.

Pedal movements are for automatic transmission vehicles. The driver model does not handle gear shifting.

In general, the speed decision model issues an acceleration command when the vehicle is required to slow down or stop for an event ahead and otherwise issues a velocity command.

When a velocity command V_{cmd} is received from the speed decision module, the following commanded acceleration A_{cmd} is computed:

$$A_{cmd} = (V_{cmd} - V_{est})/\tau_v \qquad (35)$$

where

V_{est} is the estimated vehicle velocity,

τ_v is a velocity time constant, and

$|A_{cmd}|$ is limited to Ax_{nom}.

The acceleration command—either computed as above or provided directly by the speed decision module—is then filtered as follows to provide a commanded rate of change of the pedal P_{rate}:

$$P_{rate} = (A_{cmd} - Ax_{est})/(G_a\,\tau_{acc}) \quad \text{if the accelerator pedal is being operated, or} \qquad (36)$$

$$P_{rate} = (A_{cmd} - Ax_{est})/(G_b\,\tau_{br}) \quad \text{if the brake pedal is being operated} \qquad (37)$$

where

Ax_{est} is the estimated longitudinal acceleration,

G_a is the accelerator pedal gain,

τ_{acc} is a time constant associated with the accelerator pedal, and

G_b and τ_{br} are similar parameters associated with operation of the brake.

The accelerator and brake gains are constants approximating the change in speed (m/s) per unit of pedal deflection, where 1.0 represents a maximum deflection. The time constants are selected to provide a subjectively satisfactory system response (i.e., timely but minimally oscillatory). The magnitude of the commanded rate of pedal movement is restricted to a maximum value specified by the user (e.g., maximum rate of full deflection in 1/2 second used in DVM testing to date).

The resulting command is delayed by the assumed driver delay (typically, 0.2 s) to yield a delayed pedal rate. The accelerator pedal displacement is incremented during the simulation update interval according to this pedal rate if the accelerator pedal is currently being controlled. Brake pedal displacement is otherwise incremented.

A pedal transition is initiated whenever:

- A negative pedal rate is commanded signifying further deceleration.
- The brake pedal is being controlled, the pedal is at zero displacement, and a positive pedal rate is commanded signifying further acceleration.

We suggest that an optimization approach similar to that used in the current DVM be pursued in a subsequent model development effort. This assumption represents a worst-case driver behavior and thus provides the most critical test of the highway design from a safety standpoint.

With transition, a counter is incremented according to the pedal transition time (user specified). When the speed control module is re-entered, the count is decremented, and the module is exited if the count has not reached zero. Control is switched to the other pedal after transitioning is completed.

Speed and throttle must be initialized to reflect the vehicle state at the start of the simulation. In particular, the influence of posted speed, nearby curves and stop signs, and the possibility of starting in a curve must be considered.

The following variables are defined:

a_{des}	= desired initial acceleration
ax_{nom}	= nominal acceleration
ay	= lateral acceleration
ay_{max}	= maximum allowable lateral acceleration
V_{free}	= driver’s preferred (free) speed
V	= temporary speed variable
V_c	= curve negotiation speed
V_{des}	= desired initial speed
R	= effective curve radius (positive number)
D	= temporary distance variable

The pseudo-code in figure 7 demonstrates the logic to be implemented.

```
{
set brake position to zero
set regulating acceleration
ades= 0.0
Vdes= Vfree

if (driver obeys posted speeds)
Vdes= min(Vfree, initial posted speed)

if (starting in a curve)
{
ay= lateral acceleration factor/R1/2
ay= min(ay, aymax)
V= (ay * R)1/2
Vdes= min(V, Vdes)
}

if (road contains stop signs)
{
D= distance to nearest stop sign
V= sqrt(2* D * axnom)
if (V < Vdes)
{
Vdes= V
ades= - axnom
}
}

for each horizontal curve ahead
{
D= distance to curve
V= sqrt(Vc2 + 2* D * axnom)
if (V < Vdes)
{
Vdes= V
ades= - axnom
}
}

set actual and estimated speed to Vdes
set actual and estimated longitudinal acceleration to ades
interpolate pedal position from table of vehicle parameters vs. speed
}
```

Figure 7. Pseudo-code for calculating speed control.

VEHICLE DYNAMICS MODEL (VDM)

The VDM included in the DVM is based on the vehicle dynamics analysis, non linear (VDANL) model, which is intended for the analysis of passenger cars, light trucks, articulated vehicles, and multi-purpose vehicles. At present only the passenger car and Class 8 tractor trailer are simulated in the DVM.

A detailed description of the VDM is beyond the scope of this document. A brief review of the principal features of this model is given here, abstracted from material provided by the VDANL developer. The reader is referred to Allen et al.[(2)] for additional details.

Model equations cover the full range of lateral/directional and longitudinal motions up through large angles experienced in spin out and rollover. The vehicle model includes components for sprung and unsprung masses, suspension, steering, braking, power train, drive train, and tires. The model includes a comprehensive tire model and properly accounts for the effects of maneuver-induced load transfer. The vehicle and tire models are based on past research and have been extensively validated.

Major elements of the VDM include:

- **Tires:** Characteristics of these play a dramatic role in vehicle dynamics since they respond to vehicle maneuvering. The tire model generates lateral and longitudinal tire forces and aligning moments as functions of normal load, slip, and camber angle and includes appropriate interactions between these input variables including force saturation.
- **Suspension:** Composite suspension characteristics are designed to represent wheel steer and camber motions relative to the sprung mass and squat/lift forces resulting from tire ground plane forces acting on the suspension geometry. Wheel steer also arises from compliance in response to tire side force and aligning torque.
- **Steering:** This model includes Ackerman steer effects and compliance and a composite second order characteristic to simulate steering dynamics in response to steering and aligning torque inputs.
- **Power and Drive Train:** This model includes engine, transmission, differentials and torque splitting between the front and rear axles. Front, rear, and four-wheel-drive can be accommodated. (Defaults are front wheel drive for the passenger car and both drive axles on the truck tractor.)
- **Brakes:** This model includes simulation of vacuum boost run-out and a nonlinear proportioning valve between the front and rear axles. Also includes a generic anti-lock brake system. Truck brakes include trailer pneumatic lag and fade due to overheating.

Vehicle characteristics are specified in a set of text files that are provided with the IHSDM software.

Outputs of the VDM include the location of the vehicle in geographic coordinates, vehicle heading, path (i.e., lateral offset from lane center), and other vehicle state variables (e.g., yaw rate and longitudinal and lateral accelerations).

GENERAL SPECIFICATIONS

The following are additional specifications that do not specifically correspond to any of the above components.

Halt Simulation upon Vehicle Rollover

The DVM currently computes the lateral load transfer at each simulation interval. The simulation should halt with an appropriate error message whenever this variable is equal to or greater than 1.0 or equal to or less than -1.0.

Definition of Off-road Condition

The Battelle Team conducted a mini user requirements analysis (URA) in an attempt to identify an appropriate definition for the off-road condition. Representative end-users of the DVM software were asked to provide the Battelle Team with both definitions for and operational uses of the term "off-road" condition. The results from those participating in this analysis were varied, ranging from defining off-road as the inside of a tire being outside the paved section of roadway to the entire vehicle being outside the paved roadway.

The intent of defining an off-road condition in the DVM is both to identify a situation where the driver can be considered to have lost effective control of the vehicle and define a condition where the validity of small-signal linearization adopted in certain computations is in question. (Small-signal approximations should be valid as long as the vehicle remains relatively close to lane center.)

Accordingly, an off-road condition should be defined as a condition in which all tires are entirely off the paved section of roadway (including paved shoulders). When such a condition occurs, the simulation should be halted with an appropriate message. In the case of a Class 8 truck, an off-road condition is to be identified if all tractor wheels are outside the paved section.

If an off-road condition is identified, the simulation is halted with an appropriate message shown to the user.

Treatment of Curves that are Close Together

The vehicle tends to run off the road when reverse curves are too close together and the driver is trying to cut the curve, especially when the entry point of the second virtual curve is reached before the exit point of the first virtual curve.

Tests were performed using various combinations of horizontal curvatures and separations between successive curves in an attempt to find ways to modify the degree of curve cutting (and therefore the location of the virtual curve entry and exit points) to avoid predicted steering problems. No such modification scheme was found that would consistently produce reasonable steering behavior for close curves. It was noted, however, that reasonable steering behavior was predicted when curves were separated by at least 10 m.

The recommended solution to this problem, if there is at least one pair of curves separated by less than 10 m, is to provide a message to the user at the beginning of the simulation listing each pair of curves separated by less than 10 m, and allow the user the option of continuing or halting the simulation. For simulations involving multiple trials, this message and option should be presented only at the beginning of the first trial.

SPECIFICATION FOR MODIFYING THE DEVELOPMENTAL DVM

Two modifications of the DVM have been required to facilitate calibration of the heavy vehicle: (1) additions to the output data file and (2) capability for user-programmed controls.

Additions to the Output Data File

In order to show the path followed by the heavy vehicle trailer in a horizontal curve, the DVM also includes positions of the outside trailer wheels in the primary output data file (e.g., a file having a name like "analysis.slowtruk.i.csv").

The output data file has been expanded to include the stationing and lateral location of eight wheel positions. The corresponding user-friendly names for the wheel variables (contained in the third row of the data file) should be s-wheel0, s-wheel1, etc., for stationing and y-wheel0, y-wheel1, etc., for lateral position The program names for these variables (contained in the second row of the data file) are at the discretion of the program developer. Lateral positions are given as the distance from lane center in the expanded output data file.

User-Programmed Controls

The capability for the user to override the driver's control response in the DVM with a pre-programmed control response is required for calibration driver parameters when a new vehicle is to be explored. A developmental version of the DVM was suggested in which the user may independently specify the control authority (driver or model user) for wheel, pedal, and brake. The control profile specified by the user consists of one or more segments of constant control in which each segment is specified in terms of duration and control value. Because vehicle response is time based, time rather than station serves as the independent variable.

After the user requests the simulation to commence, the developmental DVM reads a comma-separated file, UserDriverControls.txt, with the following format:

```
wheelController, pedalController, brakeController
wheel, pedal, brake, startTime, stopTime
...
wheel, pedal, brake, startTime, stopTime
```

where

```
String wheelController = {"User," "Driver"}
String pedalController = {"User," "Driver"}
String brakeController = {"User," "Driver"}
double wheel
double pedal
double brake
double startTime
double stopTime
```

If the first line of the file contains the string *Driver,Driver,Driver*, the remainder of the file is ignored, and the DVM proceeds as normal, where all controls are calculated by the driver model. If one or more of the strings in the first line is *User*, the second line of the file is read, and the values corresponding to all controls designated as user override the values computed by the driver model. Values associated with a driver control do not override the DVM-computed values. The program terminates with an appropriate error message if the value for *startTime* is not zero, or if the value for *stopTime* is less than the start time.

If the file contains only two lines of text, the final value of the second line serves as the stop time for the simulation. If the file contains a third line, control and timing variables are read. The simulation halts with an error message if either the start time is not identical to the previous stop time or the stop time is less than the start time. This procedure is repeated until there are no further lines of text in the input file, in which case the final stop time serves as the stopping time for the simulation.

If the simulation is run with partial or full *User* control, the simulation halts with an error message if the end of the road is reached before the current stop time.

Internally, the procedure for using these control data is as follows:

> Store these data in an internal lookup table. Right before calling VDANL, refer to the lookup table to see what values should be used at the current time. For each variable being controlled by *User*, override the calculated values with the file values; otherwise use the values calculated by the driver model.

DVM PARAMETERS THAT ARE SELECTABLE

The default setting of driver-related parameters in the DVM is intended to represent the behaviors of drivers who are attentive, well-trained, and driving under normal nonemergency conditions on two-lane rural highways in the absence of other traffic. Accordingly, the model generates predictions of acceptable vehicle control for even severe highway geometrics. The DVM does not treat turning at intersections.

The one exception to this rule is the long-tangent treatment of SD limitations discussed previously, but this could be modified to reflect more conservative driving behavior. By modifying certain driver-related parameters, however, one can explore degradations in driving performance resulting from one or more types of information-processing impairment.

The following discussion is organized as follows: (1) Options Selectable by the User, describing the default operation of the DVM, and (2) Options Selectable by the System Administrator, in which manipulations of certain independent model parameters can be made with the existing DVM implementation to explore nonoptimal driver behavior.

Options Selectable by the User

The DVM allows the user to select among sixteen sets of driver configurations which specify the vehicle being driven (passenger car or tractor-trailer), the nature of the simulation (deterministic or stochastic), and certain driver behaviors. Table 2 lists the sixteen standard configurations provided in the DVM. The user may specify additional configurations via the Administration Tool (also listed as Appendix A).

Table 2. Standard driver configurations.

Configuration	Vehicle	Driver Type	Cuts Curve?
Deterministic nominal-center/Taurus	Passenger car	Nominal	N
Deterministic nominal-cutcurve/Taurus	Passenger car	Nominal	Y
Deterministic aggressive-center/Taurus	Passenger car	Aggressive	N
Deterministic aggressive-cutcurve/Taurus	Passenger car	Aggressive	Y
Deterministic nominal-center/truck	Truck	Nominal	N
Deterministic nominal-cutcurve/truck	Truck	Nominal	Y
Deterministic aggressive-center/truck	Truck	Aggressive	N
Deterministic aggressive-cutcurve/truck	Truck	Aggressive	Y
Stochastic nominal-center/Taurus	Passenger car	Nominal	N
Stochastic nominal-cutcurve/Taurus	Passenger car	Nominal	Y
Stochastic aggressive-center/Taurus	Passenger car	Aggressive	N
Stochastic aggressive-cutcurve/Taurus	Passenger car	Aggressive	Y
Stochastic nominal-center/truck	Truck	Nominal	N
Stochastic nominal-cutcurve/truck	Truck	Nominal	Y
Stochastic aggressive-center/truck	Truck	Aggressive	N
Stochastic aggressive-cutcurve/truck	Truck	Aggressive	Y

where:

“Nominal” approximates the average response characteristics of the test drivers.
“Aggressive” approximates the 85th percentile driver.
Not cutting the curve means the driver attempts to maintain lane center in horizontal curves.
Cutting the curve means the driver tracks to the inside of horizontal curves.

Deterministic configurations assume the absence of variability in driver perception and response. Repeated simulations of a given driving condition will give repeatable results.

Stochastic configurations account for perceptual and response variability as a set of noise processes acting on selected perceptual response variables. A random number generator drives the various perceptual noise processes. A series of model runs with the seed of the random number generator changed from run to run will generate a series of driver responses that allow the user to compute statistics on predicted driver and vehicle response.

Driver characteristics consist of (1) nominal-center, (2) nominal-cutcurve, (3) aggressive-center, and (4) aggressive-cutcurve. The parameters for the nominal-center car driver were obtained by matching the average behavior of 18 car drivers participating in the previous DVM study. The driver is assumed to attempt to maintain the vehicle in the center of the lane over the entire roadway. The nominal-cutcurve driver has the same parameter values as the nominal-center except that the driver is assumed to cut horizontal curves by tracking toward the inside of the curve to lessen the sharpness of the path traveled and thereby allow a higher safe speed when negotiating the curve. Lane-center position is maintained on tangent segments.

The aggressive-center and aggressive-cutcurve drivers differ from their respective nominal drivers in terms of three parameters that have been readjusted to represent the estimated 85th-

percentile driver in terms of free speed, lateral acceleration factor, and preferred longitudinal acceleration. Changes in these parameters allow the aggressive driver to cruise at a higher speed in the absence of highway geometric factors (recall that there are assumed to be no other vehicles on the road), take curves at higher speeds and tolerate greater lateral accelerations, and brake more aggressively.

Values for independent model parameters were calibrated on the basis of simulated and on-road studies of passenger cars. The primary goal of the recent DVM study was to adjust the driver parameters as needed to account for the behavior of truck drivers.

The maximum SD for these configurations was assumed to be 1,000 m. An SD this large will typically have no influence on driver behavior. The instantaneous SD, however, may be reduced during a simulation run by highway geometric factors such as sharp vertical crests. In the standard configurations the driver assumes that a long tangent lies beyond the instantaneous SD. In other words, the driver ignores all potential perils that are unseen. One consequence of this treatment may be to cause the driver to react later to a horizontal curve and brake more severely than would be the case with adequate SD.

For these standard configurations, the instantaneous desired speed is the minimum of (1) the free speed, (2) the speed allowed by a requirement to stop ahead, and (3) the speed dictated by one or more curves ahead.

The procedure for calibrating driver parameters is discussed in Section 4.

Options Selectable by the System Administrator

Users having access to the IHSDM System Administration Tool can define additional Drivers to model different assumptions about driver behavior.

Speed limits

The standard options assume that drivers ignore speed limits. The user can specify a new Driver in which posted speed limits are assumed to be obeyed. In this case, the desired speed will never be greater than the prevailing speed limit (which can be different for different segments of the highway). It may be less if the driver’s desired free speed is less than the posted speed.

Road Familiarity

As noted earlier, the DVM allows for four alternative treatments of SD limitations. The standard configurations reflect the driver’s assumption that a long tangent lies just beyond the visual range; i.e., that there are no events requiring the driver to slow down. Other treatments may be employed by defining new driver configurations.

Maximum Sight Distance

Additional Drivers can be defined with lesser value of maximum SD to reflect visibility limitations caused by weather conditions. Reducing the maximum SD may also be implemented to impose a situation in which the driver does not respond to a horizontal curve in a timely manner due to inattention or aggressiveness.

Maximum Allowable Lateral Acceleration

We assume that truck drivers will adopt maximum lateral accelerations that are less than the rollover threshold; i.e., the lateral acceleration that would cause the truck to tip over. The ratio of maximum allowable acceleration to rollover threshold provides a measure of rollover stability in a turn. On-road studies indicate that the relative stability is not constant, but varies with the loading on the truck. Specifically, drivers appear to tolerate a larger lateral acceleration relative to rollover threshold (and therefore greater risk of rollover) for loaded trucks compared to unloaded trucks.

In principle, then, the effects of truck loading on driver/vehicle performance can be explored by varying the allowed lateral acceleration as a function of truck loading, provided there are data for both the rollover characteristics of the truck as a function of load and data for driver behavior with trucks with various amounts of loading. We are aware of a University of Michigan Transportation Research Institute database that may be relevant to driver tolerance of rollover risk under various loading conditions, but more information is needed to determine the adequacy of these data for relating driver behavior to vehicle rollover characteristics.

The truck model currently included in the DVM assumes an unloaded Class 8 truck. The existing implementation of vehicle dynamics is capable of representing loaded truck via a change in values assigned to relevant parameters. Additional experimental data would be required to select parameter values for specific loading conditions.

Perceptual Bias

The default DVM assumes that there are no consistent biases associated with the driver’s perception of relevant cues. Noise processes implemented in the stochastic configurations are zero-mean. Additional Drivers can be defined to represent consistent under- or overestimation of vehicle speed, appropriate curve speed, and/or distances to stop signs and curve entry points. By assuming overestimation of appropriate curve speed or underestimation of current vehicle speed, for example, the driver can be forced to negotiate horizontal curves at higher speeds and with greater lateral accelerations and higher risk of tipping over than would be the case with the default driver. At present we have no data for selecting particular levels of bias, but this capability nevertheless allows the user to explore various “what-if” situations.

SECTION 4. VERIFICATION, CALIBRATION, AND VALIDATION OF THE DVM

INTRODUCTION

This section describes the verification tests performed on the DVM. The calibration/validation methods and results are described for the passenger vehicle and the heavy vehicle.

VERIFICATION

Verification tests performed on the individual modules of the DVM are described in this subsection. Some of these tests were performed on isolated modules. Because of the complexity of the driver model, however, much of the testing of individual models was necessarily performed via simulations of driving tasks using the full DVM. Particular emphasis is given to the speed and path decision modules, which we consider to be the most critical elements of the model from a safety standpoint. Sequentially considered in the following are: Perception, Speed Decision, Speed Control, Path Decision, and Path Control, as well as Output Data Processing.

Perception

Perception is modeled as a noisy incremental process. Whenever the driver updates an available estimate, the new estimate consists of the true simulated variable potentially corrupted by both a bias factor and additive zero-mean white Gaussian noise. The bias factor is intended to account for a consistent over- or underestimation of the variable, such as a tendency to underestimate vehicle speed. For example, a bias of 0.9 represents a 10 percent underestimation of the magnitude of the variable, 1.1 represents a 10 percent overestimation, and 1.0 represents the lack of a consistent directional error. In general, a zero-mean Gaussian random noise process is added to the perceived variable to account for both the effects of perceptual resolution limitations (e.g., thresholds), and for uncertainties that tend to scale with the magnitude of the variable. Noise processes are modeled as a Gaussian white noise shaped by a first-order filter that limits rates at which instantaneous estimation errors can change over time.

The following features of the perception module have been tested:

- Proper operation of the bias feature
- Normality and whiteness of the random noise process
- Accuracy of the standard deviation of the noise process

Bias

The bias feature was verified through a test of the complete DVM. A model run was conducted in which a bias of 0.85 was associated with estimation of own-vehicle velocity, with all perceptual variables specified to be noise free. A desired free speed of 27 m/s was specified. Analysis of the results showed that the estimate of speed was consistently 0.85 times the actual speed.

Normality and Whiteness

Tests of normality and whiteness were performed directly on the simulated noise generator. Ideally, the power density function (PDF) should be Gaussian, and linear correlations among noise samples should be zero (i.e., the process should be white).

Visual inspection of the PDF of the noise samples revealed a process that very closely resembled a Gaussian noise process. Correlations among noise samples were relatively small but, as indicated below, not inconsequential.

Tests of predicted standard deviations were performed on the perception module in a standalone mode. Measures were made for all variables of interest. Results were mixed. Most predicted standard deviations were very close to the expected values, but others differed from expected values by as much as 15 to 20 percent. Theoretical analysis suggested that these discrepancies were the result of the small degree of nonwhiteness inherent in the random noise generator. Fortunately, this error in the perceptual noise standard deviation was considered unlikely to degrade the use of the DVM as an engineering tool, and no attempt was made to search for a more error-free noise-generation algorithm.

Speed Decision

The speed decision module determines both speed and speed changes. Specifically, it determines the desired steady-state speed for situations where the driver wishes to travel at a constant speed and the deceleration and acceleration profiles when the driver needs to change speeds. Desired steady-state speed is determined by one of the following parameters:

- Driver’s preferred free speed, the maximum speed at which the driver intentionally drives.
- Posted speed, when the driver is assumed to obey speed limits.
- Speed in a curve, determined by allowable lateral acceleration.

Requirements to reduce speed include:

- Negotiating a curve too fast.
- Posted speed ahead lower than current speed.
- Stop sign ahead.
- Requirement to slow down for a curve ahead.

The driver increases speed towards the currently desired speed when there is no longer a need to travel at a lesser speed.

The speed decision module contains the following alternative user-selected treatments for driver behavior in situations in which the SD is less than the stopping distance:

- The driver is familiar with the road and knows what lies beyond. In effect, the SD limitation is ignored.
- The driver assumes a long tangent just beyond the visual range. The driver responds as if nothing lies beyond visual range requiring the driver to slow down.
- A maximally cautious driver assumes a stopping requirement just beyond visual range.

- The driver assumes road geometry beyond the SD is similar to that recently negotiated. In effect, a horizontal curve of the same geometry as the curve most recently negotiated is assumed.

These features were all tested using the full DVM as described below.

Steady-state Speed

Testing the capability of the model to obey speed limits and keep steady-state vehicle speed at or below the assumed free speed was performed using a simulated tangent section containing the series of posted speeds shown in Table 3. The driver's assumed free speed was 27 m/s.

Table 3. Array of posted speeds.

Station (m)	Posted Speed (m/s)	Posted Speed (mi/hr)	Posted Speed (km/hr)
0	30	67	108
500	20	45	72
700	25	56	90
1100	30	67	108

The following qualitative behavior is expected from the model:

- The initial speed should be about 27 m/s, despite a posted speed of 30 m/s, because the driver does not intentionally drive faster than the free speed.
- The vehicle should decelerate such that a speed of about 20 m/s is attained at station 500 and—because the next posted speed is higher—the vehicle should remain at 20 m/s until the next posting is reached.
- The driver should begin accelerating toward 25 m/s after passing station 700 and should stabilize at that speed until the next posting is reached.
- The driver should again accelerate after passing station 1,100 and stabilize at the free speed of 27 m/s.

Figure 8 shows that this expected profile is followed closely by the DVM. Over- or undershoot in speed observed just before reaching steady-state speed is a result of the lack of anticipation built into the speed decision module as discussed earlier.

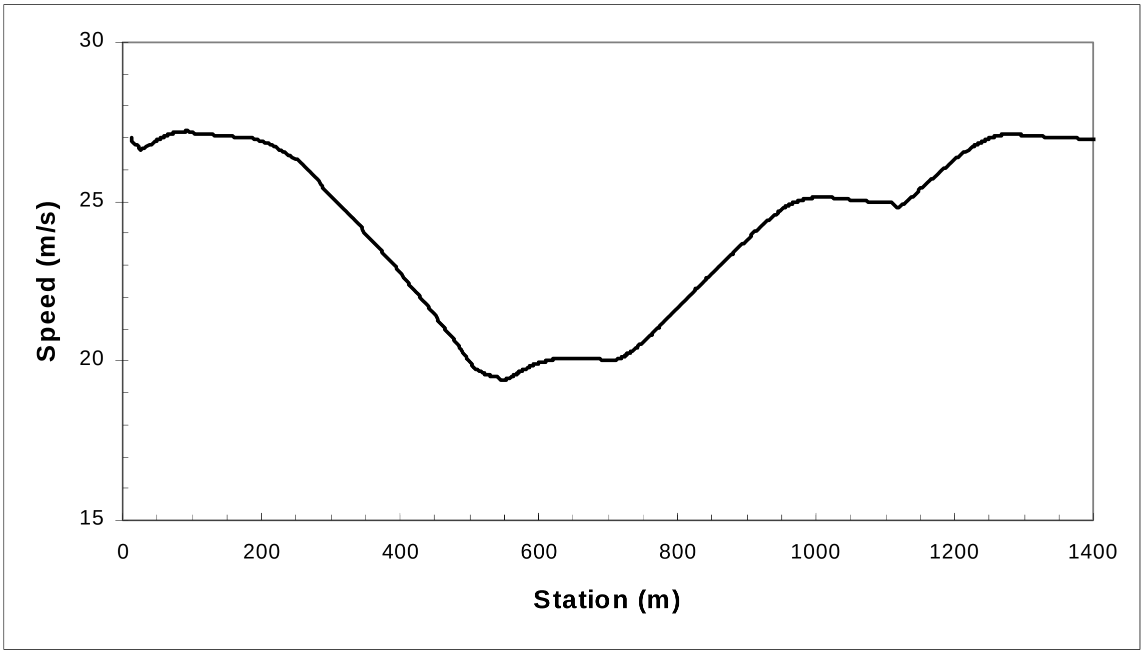


Figure 8. Effects of posted speed on predicted speed profile.

Steady-state speed in a curve depends on whether the driver is assumed to attempt to maintain lane center or to cut the curve by tracking to the inside. In the latter case, the driver is assumed to follow a curved path having a virtual radius that is greater than the geometric radius.

Verification was performed on the original model of speed in a curve in which the expected speed at curve entry is based on the assumption that the driver attempts to negotiate a curve at a speed equal to the lesser of (1) the preferred free speed or (2) the speed that yields the assumed maximum tolerable lateral acceleration. The expected curve entry speed V_{ce} is thus:

$$V_{ce} = (ay_o * R)^{1/2} \tag{38}$$

where

ay_o is the tolerable lateral acceleration, and

R is the geometric radius of curvature if the driver is assumed to maintain lane center, or the virtual radius if the driver is assumed to cut the curve.

Figure 9 shows the predicted speed profiles for negotiation of a highway having a simple curve of radius 75 m and total deflection of 20 degrees beginning at station 400. The virtual radius associated with curve cutting for this road is 120.3 m. The speeds at curve entry shown in figure 9 are very close to the theoretical values of 13.5 m/s and 17.3 m/s computed for the assumptions of maintaining lane center and cutting the curve, respectively.

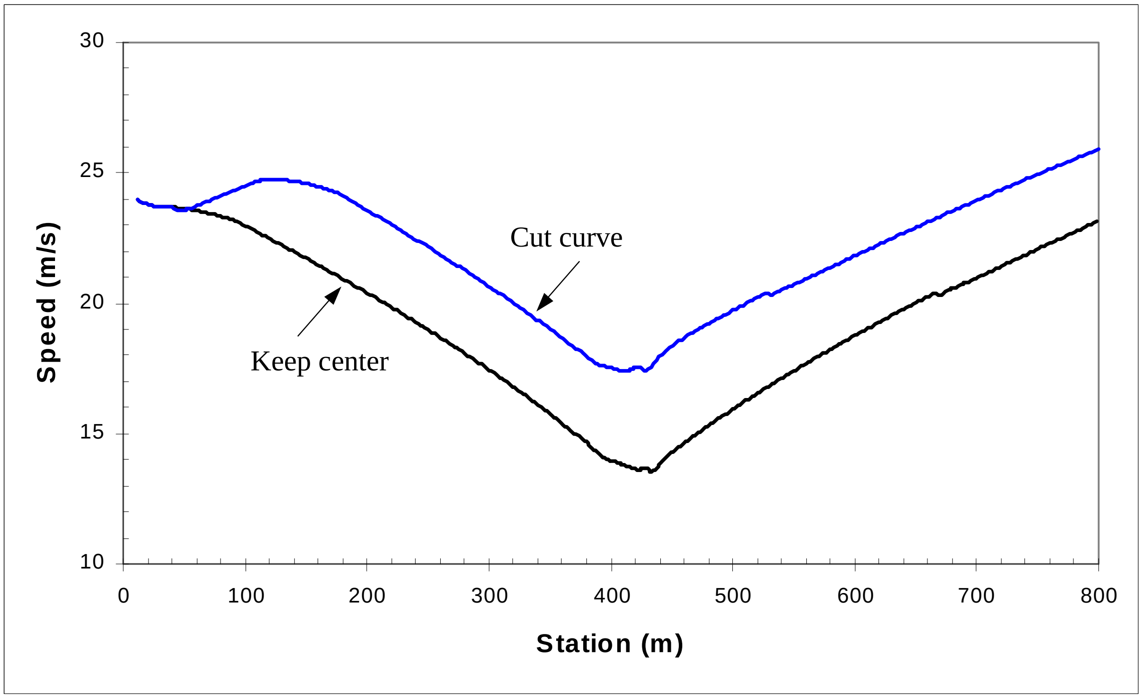


Figure 9. Speed profile for approach, negotiation, and exit of simple curve.

Because of the lack of anticipatory behavior, the speed decreases a few tenths of a meter per second after curve entry.

The initial increase in speed observed for the case of curve cutting arises from the fact that the initial speed is based on the requirements of the geometric curve. Once the simulation starts, the speed decision in this example is then based on the virtual curve.

Verification has since been performed on the current model of curve speed shown in equation 10.

Speed Reduction

A 20 percent tolerance is built into the decision to react to an overspeed once in the curve. That is, the driver will tolerate a curve negotiation speed that results in a lateral acceleration that is 20 percent greater that the allowable value. If the magnitude of the lateral acceleration exceeds more than 1.2 times the nominally allowable acceleration, a deceleration greater than the nominally preferred deceleration is applied until the speed is reduced sufficiently to be within the acceptable range. The maximum deceleration is a user-specified parameter.

This feature of the speed decision algorithm was verified via a model run in which the bias on own-vehicle speed was set to 0.85. This resulted in the vehicle entering the curve at 1/0.85 = 1.176 times the speed that would result in the assumed preferred lateral acceleration. Because lateral acceleration is proportional to the square of the velocity, the lateral acceleration at curve entry was 1.38 times the preferred value, which was seen to trigger the larger deceleration command.

When not reducing an overspeed in a curve, the driver is assumed to examine the road ahead for highway geometric elements and traffic controls that require the driver to slow down or stop. The driver computes, for each such event, the constant deceleration that would bring the vehicle to the desired speed at the desired location. If the maximum deceleration so computed is greater than the nominally preferred value, the deceleration command is given to the speed control module. Otherwise, the currently desired speed is maintained or, if the desired speed is substantially greater than the current speed, an acceleration command is given.

The deceleration ax computed for each event requiring a speed reduction is:

$$ax = (V^2 - V_e^2)/(2*D) \quad (39)$$

where

V is the current vehicle velocity,

V_e is the desired velocity associated with the event, and

D is the distance to the event.

Conversely, the distance at which an initial acceleration command will be given to the speed control module is:

$$D = (V^2 - V_e^2)/(2*ax_o) \quad (40)$$

where ax_o is the nominal (threshold) deceleration.

The speed reduction properties of the DVM were verified in a number of test cases. Illustrated here is a test case using a simulated highway with a reverse curve having the properties shown in Table 4.

Table 4. Properties of the simulated reverse curve.

Radius (m)	Direction	Length (m)	Entry Station (m)
200	Left	300	300
100	Right	100	650

Assuming a preferred acceleration or deceleration of 0.5 m/s/s, the following behavior is predicted from equations 39 and 40:

1. The vehicle starts slowing down at station = 71 m with a deceleration of 0.5 m/s/s.
2. Entry velocity for the first curve is about 22.4 m/s.
3. The vehicle resumes slowing down at station = 400 with the preferred deceleration.
4. The entry velocity for the second curve is about 15.8 m/s.
5. The vehicle accelerates to the desired free speed (27 m/s) at the rate of 0.5 m/s.

Because the second curve is substantially sharper than the first curve and follows closely after the end of the first curve, the deceleration for the second curve is expected to begin before the first curve is exited.

Figure 10 shows that the DVM predicts a speed profile that is very close to the expected behavior. The major discrepancy between theory and DVM predictions is that the deceleration begins around 20 m after expected and the deceleration reaches a magnitude slightly greater than the preferred deceleration.

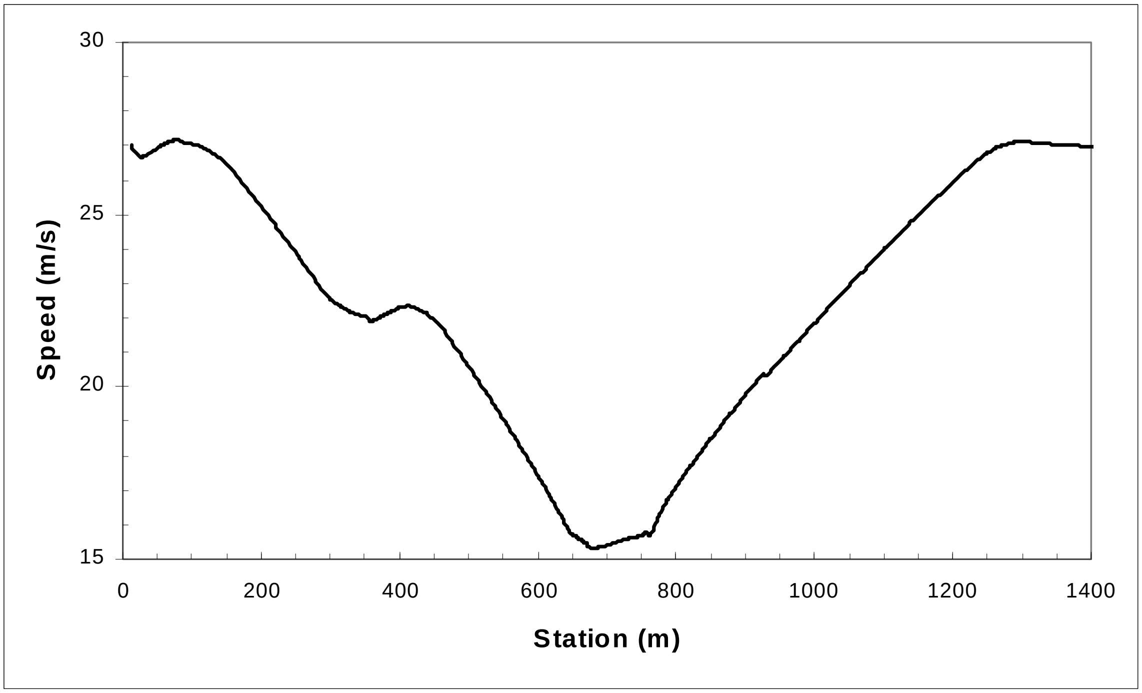


Figure 10. Speed profile for closely-spaced reverse curve.

This behavior does not reflect an error in coding but is a consequence of the linear models used in the speed control algorithms as discussed earlier. When approaching the first curve, the DVM commands a deceleration at station 71 as expected. Because of the time required for the driver to release the throttle and apply the brake, the vehicle continues to accelerate for a short distance after the command is issued. Because the vehicle has not immediately begun the desired deceleration, the DVM computes a somewhat larger deceleration requirement at the next simulation interval. The commanded deceleration subsequently reaches a steady value which, of necessity, must be slightly greater than the preferred deceleration. This somewhat larger than preferred deceleration is in order to reach the desired speed at curve entry.

Speed Control

Figures 8–10 are consistent with proper operation of the speed control module. This is clear because the decision and control modules must be performing properly in order to obtain the expected speed profiles. To further test the speed control module, and to test the ability of the DVM to handle grades in a reasonable manner, an additional test was performed using a simulated highway having a grade profile shown in Table 5. Vertically curved segments of 100 m each allowed smooth transitions between the tangent segments shown in the table. This test road had no horizontal curves.

Table 5. Simulated grade profile.

Station	Grade
0–400	0%
500–900	–5%
1,000–3,000	0%

For the vehicle speed specified for this simulation (27 m/s) the transition from a flat road to a –5 degree grade began at about 14.4 seconds into the simulation, and the subsequent transition to a level road began at about 32.8 seconds.

Figure 11 shows the throttle and brake responses to the two transitions. Of note, the throttle response occurring at the beginning of the simulation arises from the initial slight loss in vehicle speed due to the way the vehicle model is initialized.

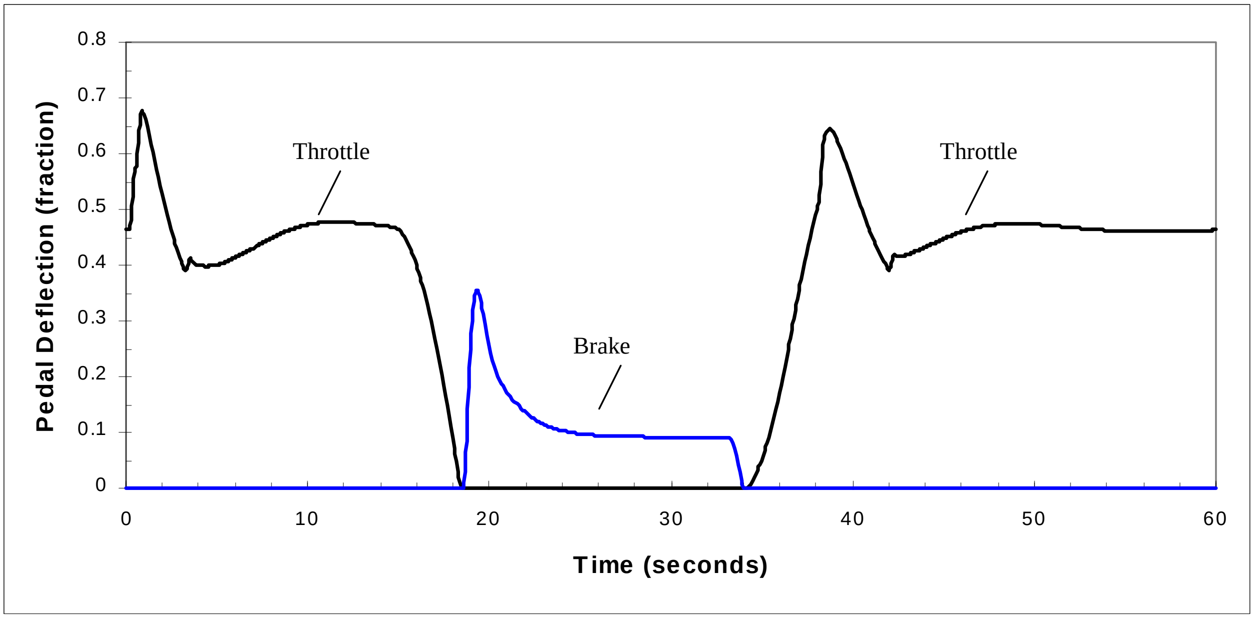


Figure 11. Effect of grade changes on model predictions: Pedal deflection.

As the road transitions to a –5 percent grade, the throttle smoothly decreases to zero and the brake is shortly thereafter applied. (Recall that the transition time between pedals is set to a negligible value because of the lags built into the linear control strategy.) The brake response—which is scaled so that it may be shown concurrently with the throttle—exhibits a single overshoot and settles smoothly to the steady value appropriate to the grade. Upon transitioning to a level road, the brake is smoothly released and the throttle settles to the original steady value after a slight oscillatory response. Both the brake and throttle responses are consistent with good linear control behavior.

Figure 12 shows that speed was regulated to within about 0.7 m/s of the desired value for this example.

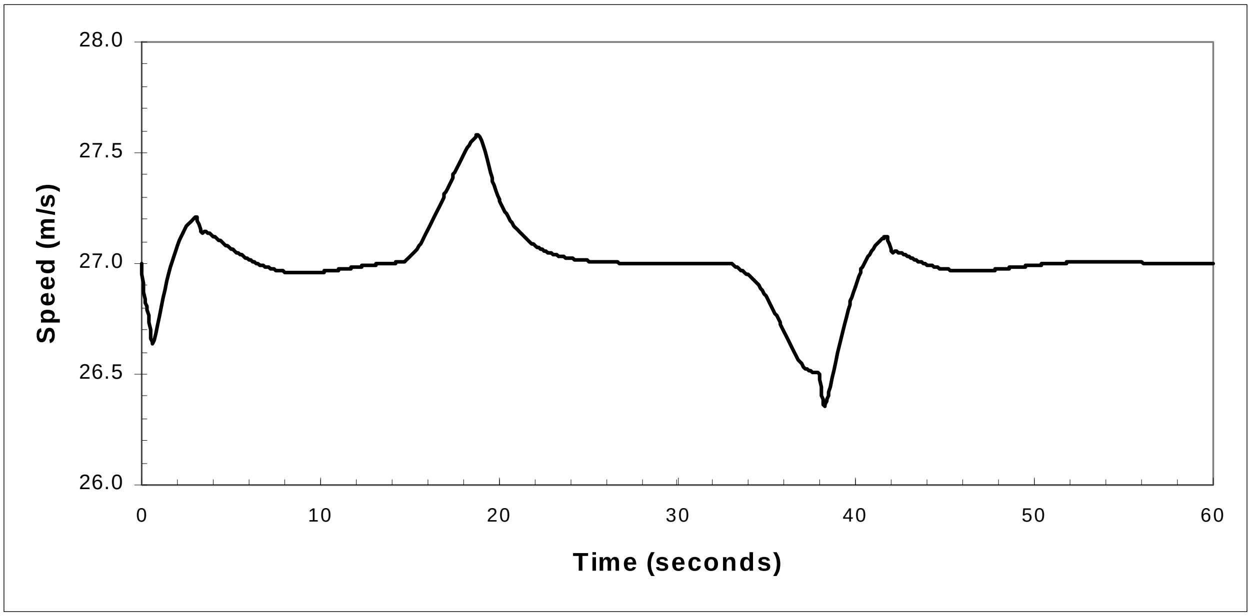


Figure 12. Effect of grade changes on model predictions: speed.

Path Decision

The path decision module generates a commanded path behavior reflecting assumptions concerning the driver's cornering strategy. If the driver is assumed to effectively flatten a horizontal curve by cutting the curve (tracking to the inside), this module generates a commanded path that approximates an idealized circular path through a curve with a larger radius of curvature than the geometric curve. As discussed previously, curve cutting was implemented by applying correction terms to the path error (i.e., deviation from lane center), drift, and yaw-rate error. The vehicle is commanded to track center of the lane when the driver is not assumed to cut curves or is not in the vicinity of a curve.

The ideal path to be followed is either lane center, when the driver is assumed to always intend to maintain lane center, or the lane deviation described by the theoretical path correction term. Because of lags and other realistic physical limitations of the driver's control behavior, we cannot expect these ideals to be met perfectly. Because of the complexity of the driver model, however, we do not have a theoretical basis for predicting precisely what the lane deviations should be, other than by running the DVM. Verification of the path decision module, therefore, is based on the extent to which the predicted lane deviations differ from the ideal when the driver has good information (i.e., no perceptual noise or bias). If these deviations are small relative to the maximum lane deviation that allows the wheels to remain within the lane (one-half the lane width minus one-half the vehicle width), we conclude that the DVM is performing the required task of effective lane tracking and that the module may be considered to be verified.

Figure 13 shows the predicted path profiles for the two conditions represented above in figure 9: keeping lane center or cutting the curve for a single curve of radius 75 m and 20 degrees total deflection. The abscissa is expanded to highlight the section of the road containing the curve where lane deviation is expected to be nonzero. Deviation from the ideal paths for both assumptions are on the order of 0.1 m in the curve. Following curve exit, where the vehicle is expected to be near lane center, the maximum predicted lane deviation is around 0.075 m for the keep-center assumption and around 0.15 m for the curve-cutting assumption. We interpret from these relatively small errors that the combination of the path decision and path control modules are working as expected.

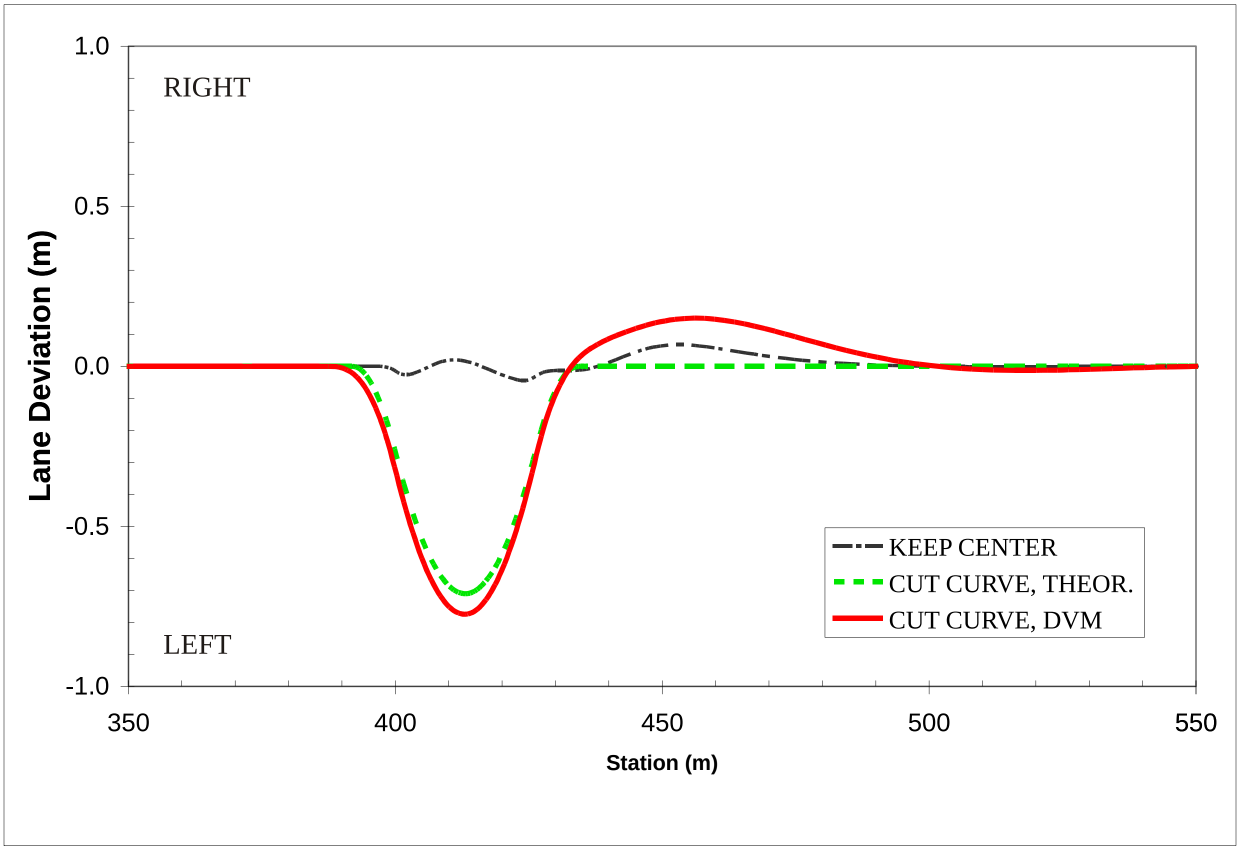


Figure 13. Effect of lane-keeping assumption on predicted lane deviation.

Path Control

Figure 13 test results are consistent with proper operation of the path control module. Two additional tests were performed on this module. First, values of the four control gains computed in this module were examined to verify their correspondence with the values obtained by hand calculations. Second, a simple constant-speed, path-correction task was simulated to verify that the response time was consistent with the effective response delay based on theoretical calculations. These additional tests, together with those described above, supported the proper operation of speed control.

Output Data Processing

The DVM currently produces two output files. One file is a frame-by-frame recording of key system variables, including vehicle states, driver controls, highway parameters, and the driver's estimates of key system states. If multiple trials are performed in a single session, the data from each trial are stored back-to-back in the same file. The other file contains summary performance statistics, consisting of probabilities of exceeding specified limits for selected performance variables.

Validation of all the output was conducted by comparisons with manual calculations. On the basis of the data contained in the frame-by-frame recordings, hand calculations were performed on the data provided in a session of a few trials to verify the computations of means, standard deviations, and the probabilities extrapolated from these calculations. The statistics contained in the summary performance file agreed with these calculations.

TEST SOFTWARE IMPLEMENTATION FOR THE HEAVY VEHICLE

This section describes the methodology and results for the test software implementation for the heavy vehicle. There were three key objectives in testing the DVM:

- Evaluate whether the DVM functioned and ran as it was designed.
- Note functional revisions that would improve the DVM.
- Identify other areas of improvement to the presentation of the data in the DVM.

Methods

Seven design scenarios were developed to test the software implementation of the functional specifications for the heavy vehicle. The testing utilized these scenarios to test the boundaries of the DVM through application of real-world design problems, such as curve-cutting problems, superelevated roadway segments, or unusual driving speeds. Each scenario consists of at least one design issue, or potential problem area, that may be flagged by the DVM.

The following assumptions were made for all of the scenarios:

Design vehicle	= WB-19 (WB-62)
Roadway type	= Two-lane rural highway
Lane width	= 3.6 m (12 ft)
Design speed	= 90 km/h (55 mi/h)
e_{max}	= 8 percent
Shoulder width	= 2.4 m (8 ft)

Each scenario was tested using the stochastic analysis to explore the likelihood that drivers would run into certain loss-of-control problems since the testing focused on whether or not drivers run into certain loss-of-control problems at the "trouble spot" in each scenario. The stochastic analysis allowed us to run 30 random drivers of each driver type through each highway scenario. (The deterministic analysis would have been appropriate in a comparison of alternatives analysis, since the same driver—or a driver with the same characteristics—would be navigating the highway segments being compared.)

During the simulation, the DVM tracks several aspects of the vehicle's performance, which can be viewed in the raw output data, and then produces a report that shows whether any of the following measures of effectiveness (MOEs) have indicated a potential safety problem at any point along the roadway:

1. Lateral offset (lane position).
2. Rollover index.
3. Friction ratio Y (lateral skid index).
4. Friction ratio X (longitudinal skid index).

Depending on the specific problem (or trouble spot) presented in each scenario, one or more of the MOEs listed above may be expected to be flagged by the DVM. The output report presents graphs of these MOEs using the mean value of all 30 drivers run in the stochastic model, as well as graphs of horizontal and vertical alignment, *K*-value, lateral acceleration, and vehicle speed. The report also provides a table that indicates the stations where any of the given MOEs exceed threshold values that warrant a yellow or red flag.

The following four driver types were used in the testing of each scenario:

1. Aggressive – center
2. Aggressive – cutcurve
3. Nominal – center
4. Nominal – cutcurve

For each of the seven scenarios, 30 simulation runs were performed using each of the four driver types, for a total of 120 simulation runs per scenario. As one might expect, the simulation runs involving either the aggressive-center or the aggressive-cutcurve driver generally resulted in more extreme values for the various MOEs. In general, the aggressive drivers typically ran the simulation 10 to 15 km/h (6 to 9 mi/h) faster than the nominal drivers, waited longer to decelerate for changes in roadway alignment, and did not reduce their speed as much through horizontal curves. The center drivers were programmed to stay in the center of their lane as they navigated curves, while the cutcurve drivers were allowed to deviate from the center path in order to increase the radius of their curve path and maintain a higher speed. No alerts in the form of yellow flags or red flags were generated from any of the simulation runs involving the nominal driver types. Therefore, the results presented in the next section are based on simulation runs involving either the aggressive-center or the aggressive-cutcurve driver type (whichever one produced the more extreme values for the MOEs).

Results

Scenario 1: Sharp Horizontal Curve at the Bottom of a Steep Downgrade

The DVM assumes that vehicles will be able to brake as needed and that drivers will be alert and attentive. That is, the DVM is not programmed to simulate brake failure or the type of excessive truck speeds that could occur along a steep downgrade. If a driver can *see* a horizontal curve, the driver will perceive and react to the alignment change in time to make appropriate adjustments to his speed to safely negotiate the curve. As such, vehicle speeds did not increase along the downgrade and, therefore, the DVM did not predict a safety problem resulting from the sharp horizontal curve.

The aggressive drivers approached the curve at a higher speed, decelerated more abruptly just prior to the curve, and traveled through the curve at a higher speed than the nominal drivers. The flag that was generated for Friction Ratio X in both the original and modified scenarios is consistent with the quick deceleration. The rollover index, lane position, and Friction Ratio Y remained within tolerable limits.

Scenario 2: Series of Horizontal and Reverse Curves

The DVM generally performed as expected in that it flagged areas of excessive lateral and longitudinal friction and undesirable lane positioning for one or more of the horizontal curves. The intention in developing scenario 2 was to create a situation that potentially violated driver expectancy by following one curve with another curve in the other direction, rather than following it with a tangent, and in come cases following a horizontal curve with a curve that has a smaller radius. However, inherent in the DVM programming is the inability to surprise a driver. That is, as long as there is sufficient SD, it is not possible to surprise a driver with an upcoming horizontal curve. It is assumed that if the driver can *see* the curve ahead, the driver will perceive and react to the curve and make appropriate adjustments to his or her speed in order to safely negotiate the curve.

The aggressive drivers maintained a greater speed throughout the roadway and decelerated more abruptly when reducing their speed, resulting in more extreme values for lateral skid index and lateral acceleration than the nominal driver.

Scenario 3: Single Horizontal Curve with Insufficient Superelevation

As expected, the lack of superelevation on a horizontal curve results in greater friction ratios—both lateral and longitudinal—which increase as the curve radius is decreased. The results of the center driver type were presented because they were more extreme in this scenario than the cutcurve driver, which makes sense given that the cutcurve driver can avoid the negative superelevation by cutting across the centerline of the road. A few unexpected results with this scenario include:

- It was expected that this scenario would be the most likely to generate a flag for the rollover index; even with the 500-m (1,640-ft) radius curve, a warning was not generated.
- It was a little surprising that the first version of the alignment (with the 1,000-m [3,280-ft] curve) did not generate any flags.

Scenario 4: Long Tangent Followed by a Sharp Horizontal Curve

The assumption behind testing this scenario is that a driver might become distracted or complacent during the long tangent and then be surprised by the sharp curve, exhibiting a delayed reaction and an improper assessment of the necessary adjustment in speed. However, the DVM cannot test for violation of driver expectancy, which was the sole purpose of this scenario. Even so, the DVM did generate flags at the beginning of the horizontal curve where one would expect there to be safety issues. The element of surprise could be simulated by defining a new driver configuration in which SD is severely limited. This option was not explored here.

Scenario 5: Single Horizontal Curve with Sight Obstructions

The objective of this scenario was to limit horizontal SD throughout a horizontal curve and determine its effect on driver behavior. The results of the simulation suggest that the driver has little difficulty and is able to negotiate the horizontal curve as though there were no horizontal sight obstruction. The SD values in the raw output data file indicate that the driver has unlimited SD before entering the horizontal curve; however, it is difficult to confirm these values without the benefit of a 3-D model or a site visit.

Scenario 6: Insufficient Lane Widening at a Horizontal Curve

The purpose of this scenario was to determine whether the additional pavement width provided in the horizontal curve would affect the driver's path, measured by lateral offset. The results suggest that the additional pavement width had no impact on the driver's path.

Scenario 7: Horizontal Curve Beginning Beyond the Crest of a Vertical Curve

The objective of this scenario was to surprise the driver with a horizontal curve just beyond the crest of a vertical curve. Limiting SD appears to be the only method within the DVM of surprising the driver. The results of this scenario show that the driver has to decelerate very suddenly after the crest of the vertical curve in order to safely negotiate the horizontal curve. This rapid deceleration corresponds to the downward spike in Friction Ratio X (longitudinal skid index). The driver has a lateral offset towards the outside of the curve before he is able to regain his intended path and cut to the inside of the curve, which is consistent with the driver not expecting the horizontal curve.

Conclusions

This section presents the overall conclusions and addresses the three key objectives from the DVM testing. It also identifies potential functional revisions that may be considered in future enhancements. The scenarios presented were developed and evaluated using version v3.02c-070327, which was the most current version available when the work for this task began. The research team recognizes that updates made to the software since that time may have addressed or negated some of the issues presented in the discussion here.

Objective 1: Evaluate whether the DVM functioned and ran as it was designed.

The DVM operated as it was designed. However, it did not always yield intuitive results. For example, none of the seven scenarios generated flags when the nominal driver type was used. This was somewhat surprising given the extreme alignment and/or problematic situation present in the scenarios. When the aggressive driver type was used, the DVM generally triggered flags at locations where the vehicle had to quickly decelerate to successfully navigate the roadway, such as at the beginning of a sharp horizontal curve. These locations are, in general, the same locations where we would expect vehicles to have problems navigating the roadway if the driver did not decelerate sufficiently. The DVM assumes, however, that the drivers are able to determine the appropriate curve speed if they can see the start of the curve. Whenever curve entry points were visible, the drivers were able to reduce speed appropriately when approaching the curve.

The Friction Ratio X variable is the most commonly flagged variable, and is typically flagged when aggressive drivers are quickly reducing their speed to negotiate a horizontal curve. Friction Ratio Y generally followed the shape of the lateral acceleration[1] graph and was only flagged in scenarios 2, 3, and 4. An alert was produced in scenario 2 at the node of a reverse curve; in the modification of scenario 3, the alert was produced at the start of the curve with no superelevation; and in scenario 4, the alert occurred throughout the length of the curve. In scenarios 2 and 3, these results were expected, but it is unclear why Friction Ratio Y was so much higher in scenario 4 than in other scenarios with curves of the same radius and drivers traveling at the same speed. Lateral offset was rarely flagged, but appeared to be triggered when a vehicle deviated from center by more than 1 m. The locations where this occurred were reasonable and expected. Rollover index was never flagged, and it is unclear what threshold values would create a rollover alert. However, the truck parameters were for an unloaded truck. An analysis of a fully loaded truck having a significantly higher center of gravity might trigger some rollover flags.

Objective 2: Note functional revisions that would improve the DVM.

When the scenarios were initially developed, the expectation of a safety problem being present was based, in many cases, on surprising the driver. However, it was noted that the element of surprise cannot be programmed into the DVM. That is, violation of driver expectancy per se is not something that the DVM will flag. Therefore, the flags that were generated in testing the scenarios were potentially influenced more by the characteristics that make up an aggressive driver (e.g., waiting until the last possible moment to decelerate, driving fast through curves) than by the alignment itself.

Currently, there are several driver options to choose from when running the DVM evaluation. While experienced users may eventually design their own drivers, the average user will probably

[1] Note: Lateral acceleration indicates acceleration in the plane of the earth, whereas Friction Ratio Y indicates acceleration in the plane of the road. Therefore, lateral acceleration and friction ratio may differ substantially when the road is superelevated.

choose from a few standard drivers available on the screen. The user should be able to view a brief description of the driver type when making this choice.

Objective 3: Identify other areas of improvement to the presentation of the DVM output reports.

In testing the scenarios, several limitations (or areas of improvement) from a user-friendliness standpoint were noted and are presented below:

- The output report shows graphs of several variables over the length of the roadway. The graphs of vertical and horizontal alignment, vehicle speed and lateral acceleration are very helpful, but Friction Ratio X and Y are not common terms that are particularly meaningful to a highway engineer. The rollover index is slightly more intuitive, but there is no indication of what values should raise concern. While it is obvious that a rollover index value of 0.5 indicates a greater likelihood that the vehicle will roll over than a rollover index value of 0.3, it still does not indicate what the likelihood is. The lateral offset variable is also helpful, but it is unclear what the offset is measured from and which side of the roadway corresponds with positive and negative values. SD would also be an important and meaningful variable that could be included in the report.
- When an evaluation is run, the output report does not provide information about the roadway characteristics beyond the basic horizontal and vertical alignment. If roadway characteristics are modified at all (for example, the lanes are widened, object offset is changed, shoulders are added, etc.), the evaluation no longer represents the saved roadway, and there is no way to determine from the output report that these characteristics have been changed. It would be helpful if there were a way to link an evaluation to the roadway characteristics for which it was run.

CALIBRATION/VALIDATION OF THE PASSENGER VEHICLE

Calibration/Validation Methods

The calibration/validation process consisted of six basic iterative steps:

Step 1. Collect on-road and, where supportive, whole-task simulator data to allow testing of certain basic assumptions and to provide a basis for calibrating the independent model parameters.

Step 2. Review psychophysical literature to determine reasonable ranges of values for independent parameters.

Step 3. Perform model sensitivity analysis to determine which parameters can be assigned default values and which need to be adjusted to reflect different driver types.

Step 4. Calibrate the model by adjusting parameters to provide a match to the experimental data.

Step 5. Compare predicted and observed behavior to test assumptions and revise the model as necessary to improve the correspondence between model predictions and experimental data.

The sixth and final step involves the use of "holdout" data to validate the model and required the team to:

Step 6. Compare predicted and observed behavior to test assumptions and revise the model as necessary to improve the correspondence between model predictions and experimental data.

Results

Table 6 and Table 7 summarize the results of the validation testing for, respectively, the tests of critical assumptions and tests of real-world predictive abilities.

Table 6. Results of validation testing for the tests of critical assumption.

Assumption Tested	Validation Results	Conclusions
Some drivers attempt to track to the inside of a curve (cut the curve) to allow a larger comfortable curve negotiation speed.	Drivers tend to cut curves in a manner predicted by the model.	Curve-cutting elements of the DVM accurately predict driver behaviors and are retained.
Drivers attempt to negotiate all curves at speeds that correspond to their individual maximum comfortable lateral accelerations.	Assumption not confirmed. Sharper curves are negotiated with higher lateral accelerations than less-sharp curves—following square root theoretical model.	Square root relationship has been implemented into current DVM.
Drivers attempt to decelerate for an event with individual preferred constant deceleration.		
1. Decelerations are relatively constant over the course of the speed reduction.	1. Curve transiting profile data revealed one driver segment following this sub-assumption, but other segments tended to follow mixed alternatives.	1. This conservative sub-assumption is not consistently violated, and should be retained in the computerized DVM.
2. The preferred deceleration is independent of the amount of speed reduction necessary.	2. A theoretically derived square-root dependency between deceleration and total desired speed change was strongly supported—with acceleration also found to follow the same relationship.	2. Square root dependency would require a not-straightforward change in the conceptual model—and is recommended for future implementation—but not in the current version of DVM.
3. Drivers increase speed at a constant acceleration that equals the absolute value of preferred deceleration.	3. Confirmed for a segment of drivers earlier seen to have a constant pattern of deceleration, but other driver segments also found to employ a constant acceleration in exiting curves.	3. Constant preferred accelerations sub-assumption should be retained in the computerized DVM.
Driver lateral-axis (steering) behavior can be adequately represented by a linear control strategy which operates on error-feedback information.	Results indicate that DVM performed within tolerances, but was slower than real-world driving with respect to quick lane maneuvers.	DVM provides a conservative representation of steering correction behavior—this is adequate for the intended application.

Table 7. Results of validation testing for the tests of real-world predictive abilities.

Predictive Capabilities on Real-World Roads	Validation Results	Conclusions
Driving performance on Washington State Route (SR) 4	Drivers had a tendency to maintain a lane center position. Curve-entry speeds are as predicted by the model, but overall curve speeds are less than predicted.	Small errors in speed profile are not significant but should be addressed in future DVM development. DVM currently provides conservative results useful for geometric evaluations.
Driving performance on Virginia SR-114 (curve #2)	On-road speed profiles match modeled speed to within one standard deviation.	DVM adequately models real-world behaviors.
Driving performance on Virginia SR-685 (curve #10)	On-road speed profiles match modeled speed to within one standard deviation. However, no curve cutting takes place.	DVM adequately models real-world behaviors, when curves are relatively isolated. DVM currently provides conservative results useful for geometric evaluations.

Parameters for the Passenger Car Driver

Two classes of driver parameters are discussed: those relating to driver preferences that are presumably under the control of the driver to a large extent, and those relating to driver limitations (primarily perceptual variability and biases) that are presumably not under the control of the driver. These parameter classes are discussed separately after a brief review of data sources. Parameters are quantified for two driver types: the average driver and the 85th percentile driver, which correspond respectively to the nominal and aggressive drivers represented in the standard DVM driver configurations.

Basis for Selecting Parameter Values

Key driver parameters distinguishing the driver types were calibrated from the data obtained in the Battelle on-road study.(3) Not all parameters were or could be defined in this manner, however. The following information sources related to human performance were relied upon to define the full set of parameters:

1. Previous laboratory studies of human performance, especially those involving laboratory manual control (tracking) tasks.(4,7) Mathematical models of human control behavior developed in these studies have provided the basis for the algorithms used in the speed control and path control elements of the DVM and have also provided specific values, or ranges of values, for some of the driver-related independent parameters.
2. Review of the perceptual literature performed under this contract provided ranges of values of variables related to perceptual limitations that were explored in a model sensitivity analysis.

3. Model sensitivity analysis performed under this contract, which illustrated the degree to which the various driver-related model parameters would influence performance predictions and which therefore allowed us to determine which parameters needed to be calibrated and which could safely be neglected.

4. On-road studies performed by Battelle under the previous contract. These studies provided data that allowed testing of the overall model structure and provided data useful in calibrating certain parameters.

5. Engineering judgment. It was necessary to make educated guesses of the values for certain parameters. Years of experience in modeling and observing human controller behavior were drawn upon to estimate values that would lead to reasonable model behavior. In all cases, testing with the DVM verified that the entire set of values selected for driver-related model parameters resulted in model predictions consistent with observed behavior.

Driver Limitations

Whenever the driver updates the estimate of a particular variable, the new estimate consists of the true simulated variable potentially corrupted by both a bias factor and additive zero-mean noise as discussed previously. Noise processes are modeled as a Gaussian white noise shaped by a first-order filter that limits rates at which instantaneous estimation errors can change over time.

Representative values for noise terms are discussed individually below. Before presenting these details, let us first review the general principles developed for selecting parameter values.

The following approach to selecting independent driver-related model parameters is based partly on previous studies of human perception and on model sensitivity analysis as discussed above. It is consistent with the DVM's primary goal of developing a tool that will allow the highway designer to explore the effects of highway geometry on speed behavior.

- A single time constant for noise filtering, tentatively set at 2 seconds, is applied to all noise processes.
- Noise scale factors, thresholds, and biases are adjusted independently for estimation of current vehicle velocity and for curve negotiation velocity. The scale factors and thresholds are to be determined on the basis of realistic driving tasks and/or laboratory psychophysical experiments. The bias terms may be determined from new or published data or may serve as user-adjusted independent parameters of the model analysis.
- A single generic noise scale factor is assigned to all lateral-axis perceptual variables and to longitudinal acceleration.
- Thresholds associated with perception of path error and yaw-rate error are kept as independent parameters and adjusted on the basis of new or published performance data only when accurate predictions of lateral-axis behavior are desired.
- Other than as described above, thresholds are ignored, and bias terms are set to 1.0 (i.e., no bias).

Parameters related to driver limitations were quantified as follows:

- **Generic scale factor:**
  The noise scaling factor associated with all perceptual variables except as described below. A value of 0.1 was selected to provide path variability consistent with data obtained in the Battelle on-road study.
- **Generic filter time constant:**
  The filtering time constant applied to all noise processes. The value 2.0 was selected based on engineering judgment.
- **Curve noise constant:**
  The noise scale factor associated with estimation of the appropriate negotiation speed for the curve ahead. Because the driver's ability to estimate this speed is assumed to degrade with increasing distance to the curve, the corresponding noise scale factor is computed in the DVM as a curve noise constant times distance to the curve. The value of 1.0E-4 for this variable was selected to provide speed variability consistent with behavior observed in the Battelle on-road study.
- **All bias terms:**
  Set to 1.0 by default.
- **All threshold values**:
  Set to zero by default. Model sensitivity analysis suggests that thresholds for estimations of current vehicle velocity and appropriate curve negotiations speeds might be useful for more accurate modeling of the effects of horizontal geometry on speed decision and control. More accurate predictions of lateral-axis control might accrue from calibration of thresholds for perception of path and yaw-rate errors.
- **Velocity scale factor:**
  Noise scale factor pertaining to estimation of own-vehicle speed. The value of 0.02 for this variable was selected to provide speed variability consistent with behavior observed in the Battelle on-road study. Note that speed variability is influenced by the combined effects of velocity scale factor and curve noise constant.
- **Distance scale factor:**
  Noise scale factor associated with estimation of distance to target (e.g., curve entry, traffic control device). Model sensitivity analysis indicates that errors in estimating this variable have substantially less influence on driver behavior than errors in estimating vehicle speed and curve negotiation speed. This noise process has therefore been ignored.
- **Variables relating to optical expansion:**
  The driver is assumed to use the perceived optical expansion of an object located at the desired stopping point when estimating the deceleration required to bring the vehicle to a stop at the desired location. Because the DVM has not been calibrated for these parameters, we currently have no basis for assigning nonzero values.

Driver Preference

A number of tolerances are available to reflect the allowable errors in various quantities. A speed tolerance is provided, and two such variables are provided for acceleration: one when attempting to regulate about zero acceleration or deceleration, and another (typically larger) value for desired nonzero accelerations. These model parameters have not been calibrated against data. Until such calibrations are performed, we recommend that these variables be set to zero.

The remaining (nonzero) parameters are reviewed below. The three parameters that distinguish between the nominal and aggressive driver—lateral acceleration factor, nominal longitudinal acceleration, and free speed—are discussed in greater detail further on.

- **Obeys speed limits:**
  A logical variable such that TRUE causes the driver to adjust speed for the posted speed limit when appropriate, and FALSE causes the driver to ignore posted speeds and adopt the free velocity (discussed below) as the preferred tangent speed in the absence of geometric or SD limitations.
- **Always keep center:**
  A logical variable such that TRUE causes the driver to always attempt to maintain lane-center position, and FALSE allows the driver to cut the curve when negotiating a horizontal curve.
- **Road familiarity:**
  This parameter selects among the four assumptions describe previously concerning the driver's familiarity with the road and the strategy for driving unfamiliar roads.
- **Max rate pedal:**
  The maximum rate of brake or accelerator pedal movement, expressed as the fraction of full scale deflection per second. A value of 2.0 was selected based on engineering judgment.
- **Maximum longitudinal acceleration:**
  The maximum deceleration (g) employed after entering a curve to correct for overspeed (not intended to represent the maximum braking available in an emergency). A value of approximately four times the nominal declaration has arbitrarily been assigned to this parameter.
- **Lateral Acceleration Factor:**
  The variable *K* in the theoretical relationship between preferred lateral acceleration in a curve and curvature:

$$Ay_o = K * C^{1/2} \quad (41)$$

where

Ay_o is lateral acceleration in m/s/s, and

C is curvature in rad/m.

The value of 36 was found to provide a good visual match to the experimentally observed relation between implied curve acceleration and curvature.

- **Maximum lateral acceleration:**
  The lateral acceleration (g) assumed to be maximally tolerable by the driver when negotiating a curve. The value of 0.4 was selected to be slightly greater than the maximum implied lateral acceleration observed in the data base used for differentiating driver type (discussed below). Lower values would be expected for vehicles with substantially higher centers of gravity.

- **Nominal longitudinal acceleration:**
  The longitudinal acceleration (g) assumed to be preferred for accelerating and for normal braking. The value of 0.048 was selected as a representative value based on decelerations observed in the Battelle on-road studies.
- **Desired gain margin:**
  A parameter of the speed-control algorithm that determines the responsiveness and degree of stability of steering control. A value of 3.0 was selected on the basis of model analysis to provide a rapid but minimally oscillatory steering response.
- **Lane margin:**
  The minimum distance (m) that the driver is assumed to prefer between the wheels and the lane edge when cutting the curve. A value of 0.3 m is currently used.
- **Free velocity:**
  Preferred speed (km/h) when not limited by highway geometry, traffic control devices, or SD. A value of 105 was determined from analysis of the Battelle on-road data as described below.
- **Velocity time constant:**
  Time constant of 2.0 s, used in the speed control model, provides a smooth response.
- **Time delay:**
  A pure delay associated with both the speed and path control algorithms. The value of 0.2 seconds is typical of values that have been derived from laboratory studies of manual control. This parameter is considered to represent a driver limitation rather than a preference.
- **Pedal transition time:**
  The time to transition (s) between brake and throttle. On-road data suggest values in the range of 0.5 to 1 s. Because the DVM does not allow the driver to anticipate the need to switch pedals, however, a negligible value of one integration time interval has been used for analysis with the DVM.
- **Preview time constant:**
  A parameter which, when multiplied by the effective time constant of the path-control loop, determines the amount of preview associated with reacting to road curvature. Model analysis indicates that a value of about 0.8 s provides good lateral tracking in a curve.
- **Wait-stop time:**
  The time (s) required for the vehicle to remain at a stop sign before proceeding. The value of 3 s was arbitrarily selected. (A nonzero value is required to ensure that the vehicle will come to a complete stop and then proceed.)
- **Acceleration and braking gains:**
  Parameters of the speed control algorithm. Values shown were adjusted to provide smooth and responsive speed response for the passenger car model. Different values will generally be needed for other vehicle models and can be determined through analysis of the models contained in VDANL.
- **Acceleration and braking time constants:**
  Additional parameters (s) of the speed control algorithm. Adjusted as described for the associated gain parameters.

- **Maximum sight distance:**
  This SD (m) represents SD limitations imposed by factors other than highway geometry, such as weather conditions and limitations on the driver's ability to see at night. The value of 1,000 m is appropriate to daytime conditions and is considered large enough to have no impact on driver speed decision.

Quantification of Driver Types

Two driver types—the average driver and the 85th percentile driver—are defined in terms of values assigned to three driver-related model parameters: free speed, lateral acceleration factor, and preferred longitudinal acceleration. Values for these parameters, which were derived from experimental data obtained in the Battelle on-road study, are given in Table 8; their derivation is described below. Other driver-related parameters remain as indicated above.

Table 8. Parameter values for two driver types.

Driver Type	Free Speed (km/h)	Lateral Acceleration Factor	Preferred Longitudinal Acceleration (g)
Average	105	36.0	0.048
85th Percentile	114	41.3	.068

Free Speed

The average free speed for each of the 18 subjects participating in the on-road study was determined by averaging the four highest speed peaks observed in the speed profile over the entire test run. The mean and standard deviation of these 18 averages were used to estimate the 85th percentile free speed on the assumption of a Gaussian distribution. The estimated 85th percentile speed was computed as:

$$X_{85} = M + Z_{85} * \mathrm{sd} \quad (42)$$

where X_{85} is the estimated 85th percentile value, M is the sample mean, sd is the sample standard deviation, and Z_{85} is the Z-value (approximately 1.037) for which the integral under the Gaussian distribution is 0.85.

The following statistics were computed for the free speed in m/s:

Mean: 28.6

Maximum: 34.8

Minimum: 23.6

sd 3.1

85th percentile 31.8

All statistics shown here pertain to the 18 within-subject averages.

Lateral Acceleration Factor

The following procedure was employed to estimate the 85th percentile value for the lateral acceleration factor *K*:

1. Driver behavior corresponding to three horizontal curves explored in the Battelle on-road study were selected for analysis because (a) they required clear reductions in speed, (b) speed behavior in each curve was felt to be dominated by own-curve characteristics, and (c) at least 9 subjects provided reliable data. The parameters of these curves are shown in Table 9.

2. *K* was estimated from each value of implied lateral acceleration through an inversion of equation 41.

3. The standard deviation of *K* was computed for each curve.

4. The three standard deviations were averaged to provide an overall estimate of the standard deviation of *K*, and the calculation of equation 42 was used to compute the estimated 85th percentile value for *K*. The mean estimate of 36.0 obtained from visually fitting the acceleration data was used in this calculation.

Table 9. Parameters of curves selected for estimating statistics of the lateral acceleration factor.

Curve No.	Geom. Radius (m)	Virtual Radius (m)	Virtual Curvature (rad/m)	Virtual Curvature (deg/100 ft)
3	125	136	0.0074	12.8
5	146	154	0.0065	11.3
6	125	130	0.0077	13.4

Standard deviations of 6.17, 5.10, and 3.97 were computed for curves 3, 5, and 6, respectively. The mean sd of 5.08, along with the estimated mean for *K* yielded an estimate of 41.3 for the 85th percentile value.

Preferred Longitudinal Acceleration

The deceleration on curve approach and the acceleration after curve exit both exhibited speed dependencies that were modeled as a square-root relationship between acceleration or deceleration and total speed change. Because the current model structure does not contain a reliable predictive model for total speed change, acceleration and deceleration are presently treated as a constant having a value representative of those observed in the Battelle on-road experiment.

To obtain representative statistics, the mean deceleration on curve approach was computed from all estimates of average deceleration where the total speed reduction was 2.0 m/s or greater. The average deceleration associated with a given curve approach was estimated by dividing the total decrease in speed by the time over which the driver was decelerating for the curve.

Because of the relationship between deceleration and speed change, computing the standard deviation from the entire set of deceleration measurements would overestimate the variability of the deceleration about the mean deceleration associated with a given speed change. A more representative measure of acceleration variability would be the standard deviation relative to the local mean. An approximation to this metric was obtained by adjusting the model for deceleration to provide a least-squared-error match to the observed decelerations, treat the model prediction of deceleration for a given speed change as the local mean, and compute the standard deviation of all measured decelerations about their local means. The 85th percentile preferred acceleration was computed according to equation 42 using the standard deviation about the estimated local mean.

The best-fitting model for the deceleration data was:

$$ax_o = 0.245 * \Delta V^{1/2} \qquad (43)$$

where

ax_o is the estimated preferred deceleration, and

ΔV is the required decrease in speed.

The following statistics (m/s/s) were computed for average deceleration:

Mean:	0.47
Maximum:	0.92
Minimum:	0.20
sd	0.14
85th percentile	0.62

Note that the 85th percentile value corresponds to speed decrements for which the expected deceleration is around 0.47 m/s/s (0.048 g).

CALIBRATION/VALIDATION OF THE HEAVY VEHICLE

Background

Parameters related to vehicle dynamic response and driver performance limitations were quantified. Parameters remaining to be determined were:

- Guidelines for curve cutting.
- The free speed which drivers adopt on sufficiently long stretches of tangent segments where neither the geometry of the road ahead, traffic, nor posted speed limits are factors in determining vehicle speed.
- The lateral acceleration factor, which defines the relationship between curvature, speed, and lateral acceleration in a horizontal curve.
- The maximum lateral acceleration that the driver willingly tolerates in a horizontal curve.
- The nominal longitudinal acceleration—the preferred acceleration when either speeding up or slowing down.

- The maximum longitudinal acceleration that the driver will employ when braking beyond the preferred level is necessary. (The DVM is not intended to be applied to true emergency situations in which the driver applies maximum force to the brake pedal.)

Calibration and validation were originally proposed to be separate tasks, with a portion of the available on-road data being used to quantify the various independent model parameters, including those enumerate above, and the remaining held back to be used to test the predictive validity of the DVM using the parameter values determined in the calibration phase.

A study of driver behavior suitable for quantifying all the parameters listed above would require the following highway and operational conditions:

- Level tangent sections with the highest speed limits allowed, without traffic, and sufficiently long so that preceding and succeeding horizontal geometry would not affect the asymptotic speed.
- Horizontal curves of varying radii separated by long tangent sections so that the influence of a specific radius of curvature could be determined free of confounding by other geometric features.
- Portions of the study in which the drivers were instructed to brake at the maximum comfortable level, and negotiate curves at the maximum comfortable level.

Such conditions, which are highly idealized and perhaps realizable only in simulation studies, were not provided by the Virginia Tech Transportation Institute (VTTI) on-road study. Speed limits on the section of highway analyzed in this study were 45 and 35 mi/h, likely preventing the drivers from reaching their preferred free speed as defined above. Because this study did not include situations where drivers were instructed to perform maximum comfortable braking or negotiate curves at maximum comfortable speeds, maximum tolerable acceleration levels could not be determined.

The highway geometry, coupled with the speed limits, did not facilitate partitioning the test road into portions separately used for calibration and validation. Consequently, the on-road data were used to jointly calibrate and validate the DVM. To be consistent with the passenger vehicle calibration/validation procedures, the ability to predict a speed profile falling within one standard deviation of the mean speed profile provided by the test drivers was selected as the criterion for validity.

Test Route

Data from an on-road study comparing the behavior of drivers of a passenger car and a Class 8 tractor-trailer heavy vehicle were used during the calibration/validation process. The test route was a 16-km route consisting of Virginia State Route (SR) 114 and Montgomery County Route (CR) 685. Both routes are two-lane rural highways. The first leg—SR-114—was determined to provide insufficient challenge to provide adequate data for either calibration or validation. Accordingly, the calibration/validation results presented herein are based on the data obtained from 6.2 km of CR-685.

The drivers first drove SR-114 to the intersection of SR-114 and CR-685, controlled by a stop light, then turned onto CR-685. The intersection of the two routes is considered to be station 0 for this analysis, where one unit of station increment corresponds to 1 m proceeding generally north.

Global Positioning System (GPS) instrumentation was used both to determine the horizontal and vertical profiles on the test route and to allow recording of vehicle location during the test drives conducted in previous research[(3)]. During the current study phase, the roadway calibration data were found to have serious internal inconsistencies. Specifically, distances between two points on various tangent sections computed from the GPS recordings differed by varying amounts from distances between corresponding points determined from the distance-measuring wheel. Because no consistent transformation between the two methods of measuring distance could be found, VTTI re-calibrated CR-685 for this study phase. GPS recordings were converted to measurements of easting, northing, and height, all in meters. The resulting records were internally consistent, and a plot of the easting and northing measurements provided a good qualitative match to a map of the test route.

In order to provide the roadway-related inputs needed for model analysis, the roadway measurements were analyzed to determine curvature and height as a function of station. East (X) and north (Y) coordinates were determined from the GPS measurements and, where there were significant gaps in the GPS recordings, from interpolations using onboard measurements of speed and yaw rate.

Engineering drawings of CR-685 provided by the Virginia DOT, Christiansburg Residency, were used to provide a first approximation to the analytic representation of horizontal profile in terms of tangents and curves of constant radius. Adjustments were then made to improve the visual match to the road as recorded by VTTI. Graphical analysis of the recording of height versus station, derived from the GPS measurements, was employed to determine the analytic representation of the vertical profile.

Figure 14 provides a comparison of the plan views of the test route as determined from the on-road calibration effort with the analytic representation used in the DVM. The match was considered adequate to allow confidence in the estimates of the radii of the horizontal curves contained in the test road. Vertical profiles of the measured and analytic test routes are shown in figure 15.

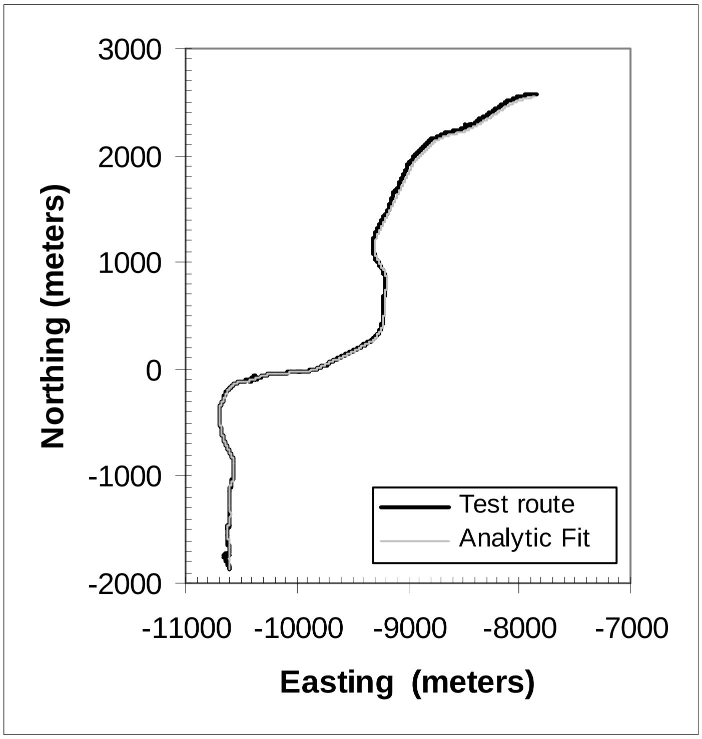


Figure 14. X/Y plot of test route.

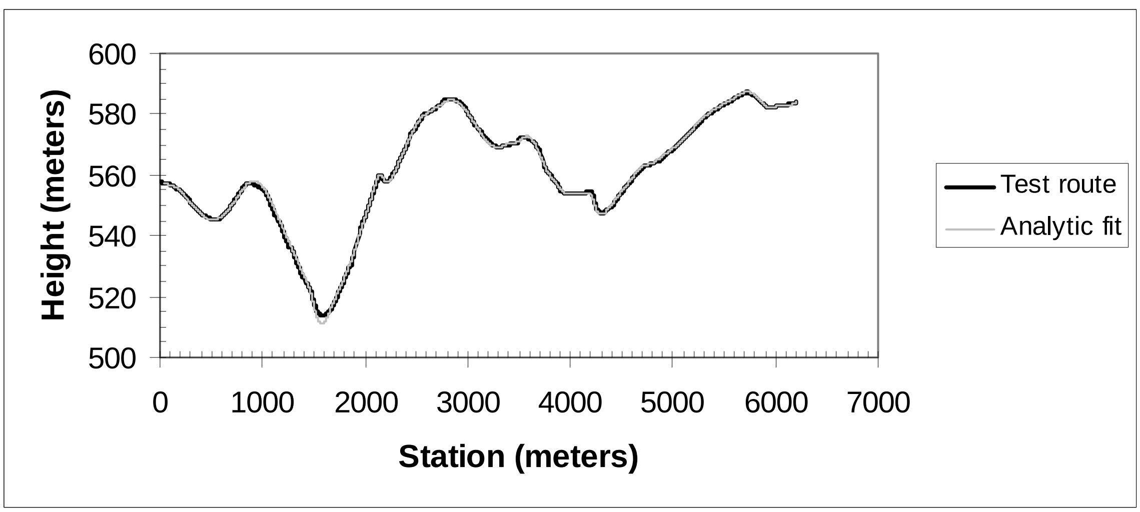


Figure 15. Vertical profile.

The posted speed for the test route was 45 mi/h (about 72 km/h, or 20 m/s) from stations 0 to 5158 and beyond station 6067, and 35 mi/h (about 56 km/h or 15.6 m/s) from stations 5158 to 6067.

On-Road Data

Five drivers participated in the heavy-vehicle portion of the on-road study. Data usable for model analysis were obtained from four of these drivers. Because there were occasions when other traffic impacted the behavior of the test drivers, not all replications could be used. Replications included in the database used for model calibration and validations are indicated by an “x” in the corresponding cell in Table 10.

Table 10. Replications of on-road data used for model analysis.

Driver No.	Rep. 1	Rep. 2	Rep. 3	Rep. 4
1	x	x	x	x
2	x	x	x	x
3		x	x	
5	x	x	x	

An ensemble-averaged (mean) speed profile was computed from the results of the first usable runs performed by each subject, and a similar mean-speed profile was computed from the final usable runs. The close correspondence between the two mean-speed profiles shown in figure 16 suggested that meaningful learning of the road characteristics by the drivers did not occur during the study with respect to speed decision-making. Accordingly, further analysis was performed using mean-speed profiles computed for each driver from all usable runs.

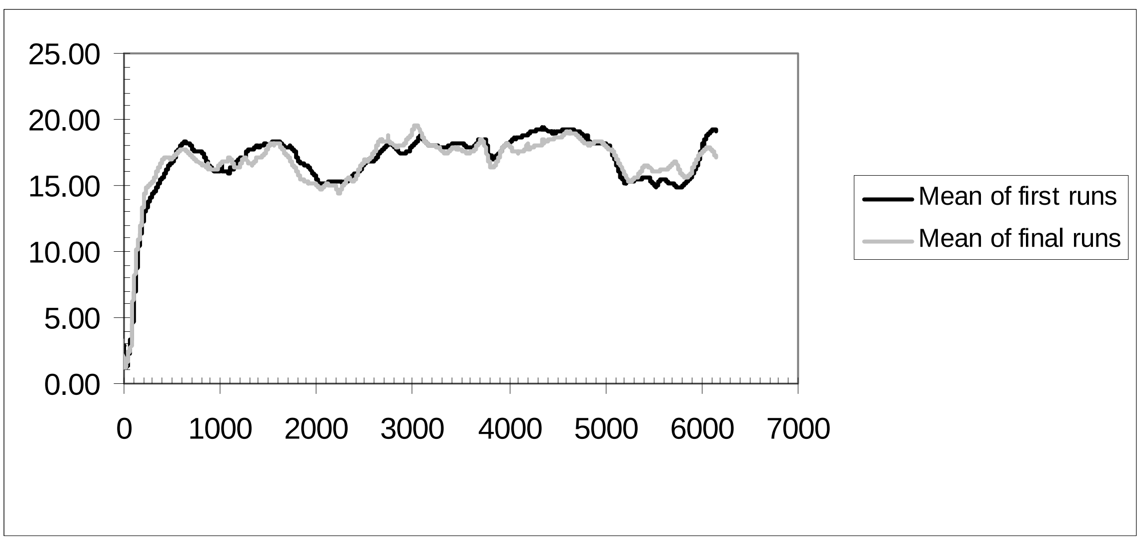


Figure 16. Mean first and last speed profiles.

Road curvature with station is shown in figure 17. Positive curvature signifies a curve to the right. Some visual correlation between the magnitude of the curve and reduction in speed can be observed, but it should be noted that posted speed limits as well as limits on the uphill acceleration capability of the vehicle also influenced vehicle speed.

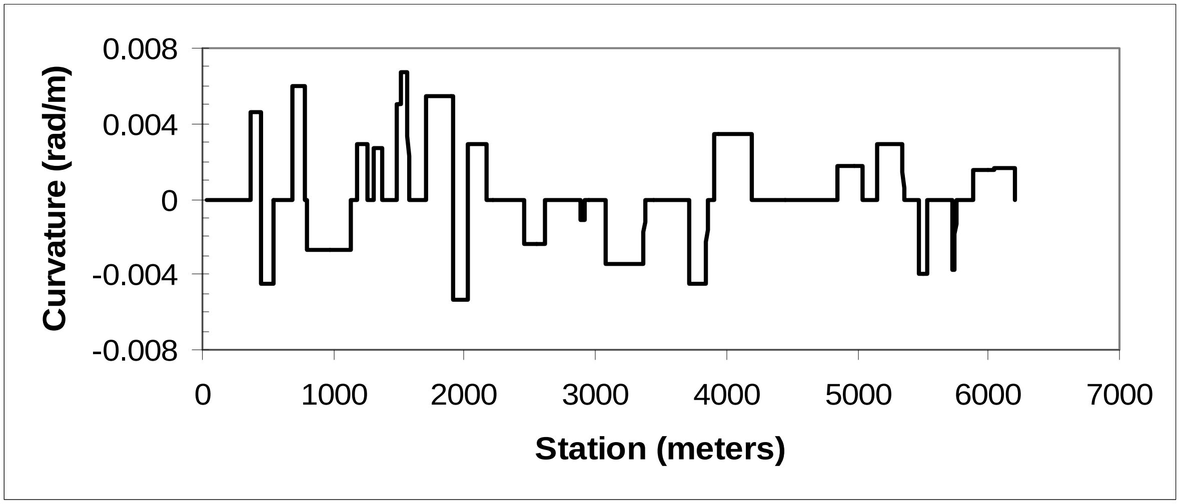


Figure 17. Road curvature.

Mean speed profiles for the four test drivers are shown in figure 18. One pair of drivers drove consistently slower that the other pair, by around 2–3 m/s, but the general trends of speed with station were similar. Figure 19 shows the overall mean speed profile along with the one standard deviation bounds.

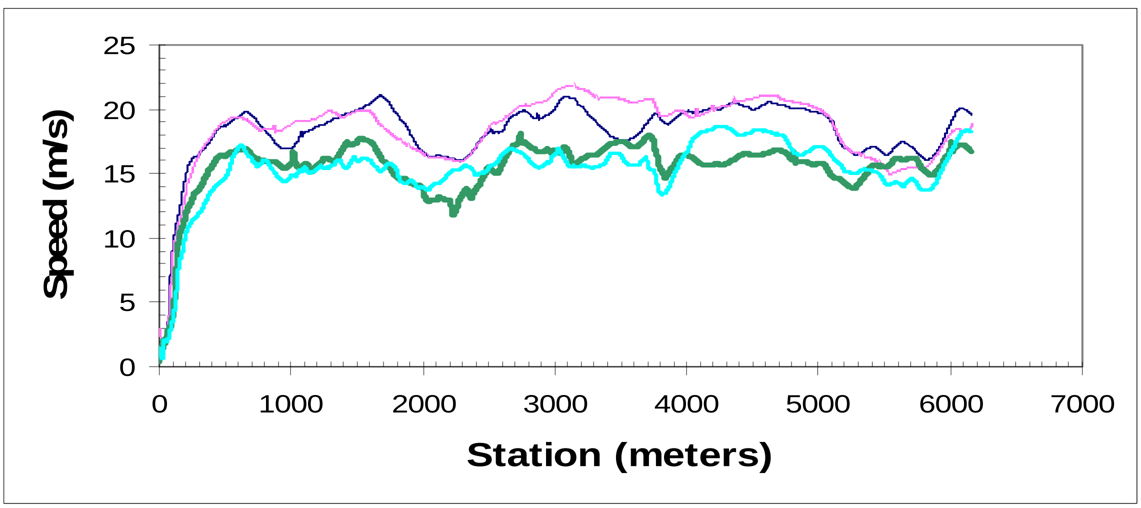
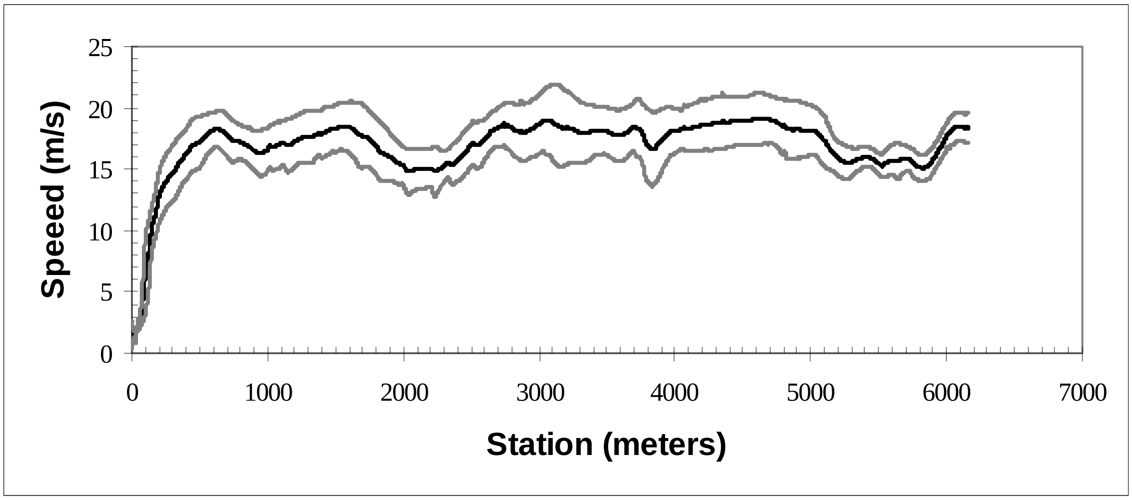


Figure 18. Mean speed profile for four drivers.



Black: Mean profile
Gray: +/- Standard deviation

Figure 19. Mean +/- standard deviation of driver means.

As noted above, the DVM allows the user to specify whether the driver is assumed to track to the inside of the curve (cut the curve) or to attempt to maintain the vehicle in the center of the lane, where lane position is defined as the distance of the center of mass of the cab from the center of the lane. In order to provide guidelines for setting this model parameter, we need to explore actual driver behavior to determine the strategy for steering a heavy vehicle (tractor-trailer) of the type considered in this study.

By cutting the curve, the driver effectively increases the radius of curvature, thereby allowing curve negotiation at a higher speed and lower lateral acceleration than by maintaining a lane-center position throughout the curve. The effect is greatest for sharp curves with small deflection (directional change) and diminishes as either curve radius or curve deflection is increased.

While the above comments apply generally to a single-unit vehicle, the driver of a tractor-trailer must consider the location of the trailer wheels when negotiating a curve. Even with the tractor maintained near lane center, the rear trailer wheels may track so far to the inside as to cross the lane boundaries. One might therefore anticipate that heavy vehicle drivers would track to the outside of sharp curves and maintain lane center for more gentle curves.

There did not appear to be a consistent curve-tracking strategy over the 6,000 m of travel. For much of the travel the truck appeared to track on the average to the right of center independent of the horizontal geometry. There is some indication that when negotiating a reverse curve, the process of negotiating the first curve tended to set up the vehicle to track to the outside of the second curve. This may have been an intentional strategy, or it may have reflected a difficulty in steering quickly enough to enter the second curve at lane center.

Calibration/Validation Methods

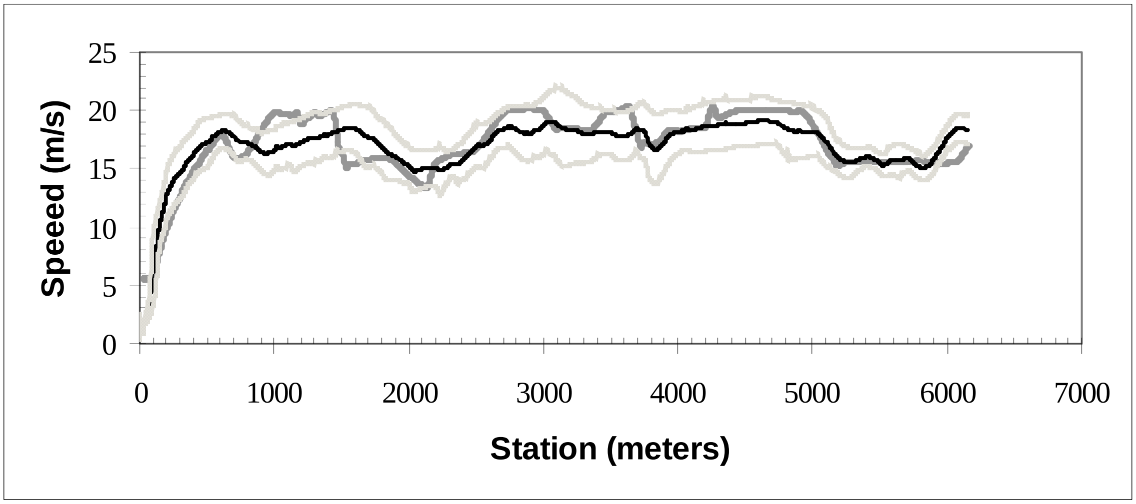
The same six iterative steps used in the calibration/validation of the passenger vehicle were used to calibrate/validate the heavy vehicle. The on-road data along with model analysis were used to determine guidelines for treating curve cutting and for calibrating the driver-related parameters of nominal longitudinal acceleration and lateral acceleration factor. As noted previously, the on-road study was not conducive to determining values for free speed and maximum tolerable accelerations for the heavy-vehicle driver.

Results

Variations in speed and lane deviation for the test route were minor. Table 11 shows the validation results for curve cutting, longitudinal acceleration, later acceleration, horizontal SD, and short tangents.

Table 11. Summary of validation results for the heavy vehicle.

Driver-related Parameters	Validation Results
Curve cutting	The outer right rear trailer wheels tracked outside the right lane boundary when negotiating the 100-m curve in both runs and came very close to the lane boundary in the 200-m curve when cutting the curve. The driver was able to cut the 300-m curve without the rear wheels crossing the lane boundary, but for the curve deflection explored here, there were negligible changes in predicted speed and predicted lateral acceleration compared to maintaining lane center. The user is advised to assume for the purposes of model analysis that the driver of a tractor-trailer type of heavy vehicle attempts to maintain lane center in the absence of lane widening at the site of the curve. (At present, the model does not accommodate the assumption that the driver attempts to track to the outside in a curve.) The model parameter *always keep center* should be set to TRUE.
Nominal longitudinal acceleration	The longitudinal acceleration and deceleration preferred by the automobile driver depends on the total change in speed. An analytic expression relating acceleration or deceleration to the magnitude of the resulting speed change reproduces the trends of the on-road data. Because the steady-state (cruising) speeds on short tangents connecting horizontal curves is expected to be less than the free speed that might be obtained on very long tangents, the preferred acceleration will generally depend on the length of the tangent and the speeds appropriate to negotiating the adjacent curves. At present, the model does not predict cruising speeds in such situations, and the user must specify a preferred acceleration that is representative of the highway environment. For the model analysis described here, a representative value of 0.032 g was selected from visual inspection of the longitudinal acceleration profiles observed in the on-road data.
Lateral acceleration factor	For the most part, the predicted speed is determined by the posted speed limits and not by the horizontal geometry. A comparison of the predicted speed profile to the vertical road profile suggests that speed was reduced in the region of station 2000 because of acceleration limits of the heavy vehicle. Inspection of the predicted accelerator profile reveals maximum pedal deflection during the period when the predicted vehicle falls below the prevailing miles per hour speed limit. Reducing the lateral acceleration factor to 20 yielded a predicted speed profile that was within one standard deviation of the experimental mean profile for almost the entire distance, as shown in figure 20.
Horizontal sight distance limitations	Selecting the full stop option (the driver assumes that an obstruction requiring a full stop lies just beyond the sight distance) for testing sight distance limitations degraded the overall match to the measured speed profile. Predicted speed variations were greater than in the previous analyses, with the speed dropping well below one standard deviation from the mean at two locations. Further study is required to determine how horizontal sight distance limitations influence driver behavior and how to model such effects.



Black: Mean speed profile of four drivers
Light Gray: Mean +/- one standard deviation
Dark Gray: Model prediction

Figure 20. Predicted speed profile when reducing the lateral acceleration factor to 20.

RECOMMENDED VALUES FOR DRIVER PARAMETERS

Recommended values for parameters related to driver preference are shown for both passenger car and heavy vehicle truck drivers in Table 12 for the nominal (as opposed to aggressive) driver. To the extent allowed by the data, these parameters reflect the on-road data used to produce the DVM. In the absence of definitive data, engineering judgment provided estimated values.

Table 12. Parameters related to driver preference.

Parameter	Function	Car	Truck
Preview time constant (s)	Path control	0.8	1.0
Gain margin		3.0	3.0
Speed time constant (s)	Speed control	2.0	2.0
Acceleration gain		0.1	0.1
Braking gain		1.0	0.5
Able to cut curve?	Path decision	T	F(1)
Lane margin (m)		0.3	NA
Free speed (km/h)	Speed decision	105	105(2)
Lateral acceleration factor		36	20
Maximum lateral acceleration (g)		0.4(3)	0.4(3)
Nominal longitudinal acceleration (g)		PD(4)	PD(4)
Maximum longitudinal acceleration (g)		0.2(3)	0.2(3)

Notes:

1. In general, it is not advantageous for the truck driver to track to the inside of the curve. More likely the driver will track to the outside of the curve to minimize the likelihood of the trailer crossing the lane boundaries—a behavior not currently handled by the DVM.
2. Data were not available for determining this parameter for the heavy vehicle. The value associated with passenger car is suggested pending further study.
3. Based on engineering assumptions in the absence of data available to calibrate this parameter.
4. Problem dependent. Values of 0.048 g and 0.032 g were found to characterize the data available for passenger car and heavy vehicle drivers, respectively. These values may be more reflective of speed limit restrictions than differences between car and truck drivers.

VALIDATION OF VEHICLE DYNAMICS MODEL FOR HEAVY VEHICLE

Both the passenger vehicle and the heavy truck components of the DVM require a VDM that can simulate the full range of lateral and longitudinal movements of the vehicle including acceleration, steering, braking, power train, drive train, and tires. For the DVM, the VDANL module was used. For the passenger vehicle component of the DVM, VDANL was used without any additional calibration or validation activities. However, the VDANL code required additional validation for heavy truck modeling.

To conduct the heavy vehicle validation, project staff from Systems Technology, Inc. (STI) used the parameter and test data collected at the Vehicle Research Test Center (VRTC) on an earlier and separate National Highway Traffic Safety Administration project. The vehicle tested at VRTC was a 1992 White-GMC truck manufactured by Volvo GM Heavy Truck, model WIA64T (two drive axles), and a 1992 Fruehauf van trailer, model FB-19.5NF2-53 (53-ft-long box trailer with two axles). This tractor-trailer combination is similar to the WB-20 [WB-67] vehicle combination. This combination is similar to, but shorter than the combination used to collect the on-road data for the DVM (a 1997 Volvo VN/48-ft van trailer).

The heavy truck validation was conducted with a standalone version of the VDANL code. The parameter development and model evaluation were conducted for the empty trailer condition (VRTC conducted empty and fully loaded trailer tests). The empty trailer condition is what VRTC has presented from their evaluation and was of most interest to the current effort. A full VDANL vehicle parameter set was developed including vehicle, drive train, suspension, braking, and tire parameters. Once the vehicle parameter sets were fully developed, the model was run through maneuvers identical to those performed with the actual vehicle. The measured test driver inputs (brake, throttle, handwheel angle, etc.) were used to drive the VDANL vehicle model. The maneuvers tested covered a broad range of vehicle operating conditions, which were set to characterize the model's static and dynamic performances and were then compared to measured dynamics. The tests included slowly increasing steer, step steer, lane change, straight line acceleration, straight line braking, and several others. Some of the test data were collected with open loop driver inputs and others were closed loop. For maneuvers with open loop driver control and multiple test runs, statistical estimates of the mean vehicle response were made and used for comparison with the VDANL results.

The VDANL model evaluation for the tractor-trailer combination produced results that were consistent with those for the VRTC model evaluation (a full report on this effort was provided to the FHWA separate from this report). The parameter set should be considered representative of this heavy vehicle class but not an exact match for any particular vehicle.

In addition to validation of the heavy truck modeling within VDANL, a number of enhancements to VDANL were completed; these included:

- Improvement to the tire rolling drag portion of VDANL.
- Implementation of engine braking systems and retarders.
- Improvement of the model's ability to start on an upgrade or a downgrade.
- Update of the thermal brake model with a newer, enhanced version of the model.
- Implementation of the bump stop model.
- Implementation of the model for damper and bump stop track widths for solid axles.
- Implementation of the ability to change tire characteristics based on roadway surface condition.
- Addition of the capability to model multi-axle vehicles and trailers.

SECTION 5. SUMMARY AND CONCLUSIONS

KEY DVM APPLICATION CONSTRAINTS

Application of the DVM is bounded by a number of constraints associated with the conceptualization and implementation of the model. These constraints include:

- The driver is experienced with the driving task in general.
- The driver makes appropriate decisions and control actions when given good perceptual information.
- The highway driving situations are typical and relatively relaxed.
- The vehicle performs properly.
- The driving task is basically limited to the operational task of regulating vehicle path and speed.

ADDITIONAL MODEL ENHANCEMENTS

Work on this project has revealed a number of areas in which the DVM could benefit from further development. The current DVM implementation would need to be modified to treat the highway conditions and/or driver behaviors discussed below.

Cruise Control and Compound Curves

The request for information on potential model enhancements has arisen largely from an inquiry concerning the potential application of the DVM to a segment of Massachusetts Interstate 95 containing a compound curve in one direction followed by a curve in the opposite direction. The compound curve consists of a lead-in curve, a central (sharper) curve of lower radius, and a lead-out curve having the same radius as the lead-in curve. The inquirer was concerned about the potential for rollover where the horizontal alignment reverses, particularly at times when speeds in excess of 80 mi/h are routine.

We deal first with the issue of speed. We assume that the concern is for drivers who maintain 80+ mi/h throughout the curves. The present implementation does not have the capability to impose this condition in a credible manner. The existing implementation does allow the user to specify a very large free speed and to assume that speed limits are ignored, but even under these assumptions the DVM would slow down for curves. In principle one could force a constant speed by specifying zero SD (the current implementation does not allow a SD less than 100 m), but then how would the driver be able to steer?

A developmental version of the DVM has been created for the purposes of calibrating vehicle lateral and longitudinal response which allows the user to specify a fixed throttle position. In this configuration, the driver continues to steer the vehicle but does not control throttle or brake. If desired, this capability could be included in the public-release version of the IHSDM.

The assumption of a fixed throttle position would not be reasonable for driving over a typical two-lane rural road with segments of varying horizontal curvatures. It might be more reasonable for highways designed to interstate standards in which curved segments are required to have relatively large radii of curvature. Even so, a fixed throttle does not guarantee fixed speed because of the accelerating and decelerating effects of down slopes and up slopes, respectively.

Incorporation of a submodel for cruise control would allow a more credible representative of actual driver behavior. In this configuration, the free speed parameter would be superseded by a minimum speed parameter, and the speed-control component of the DVM would be modified to regulate speed about this minimum speed using throttle only. Such an implementation would allow the vehicle to proceed faster than the desired speed on steep down slopes, but such behavior is representative of driving with cruise control.

Implementation of a cruise-control option in which a constant desired speed is specified for the entire run should require only a modest software development effort. Implementation of the capability for the driver to transition from cruise control to driver control of speed is not recommended at this time because of the absence of data for determining the rules for transition. Accordingly, implementation of fixed cruise control is recommended only for highways having consistent horizontal geometry; that is, situations in which a driver might be expected to leave the cruise control setting untouched over the roadway of interest.

The DVM does not properly treat speed decision in compound curves that consist of three consecutive segments of constant curvature; this condition has not yet been addressed. One remedy would be to augment the DVM to recognize such compound curves and allow the driver to cut only the central curve.

Driver Behavior on Short Tangents

Further experimental and theoretical studies are recommended for developing a general model for the speeds in tangents connecting horizontal curves. Such a model would allow the application of a model (for which data currently exist) for predicting accelerations and decelerations as functions of predicted speed changes.

Horizontal Sight-Distance Limitations

Analysis of driver behavior observed in the VTTI on-road study suggested that horizontal sight-distance limitations may have influenced vehicle speed on tangents. An experimental study of on-road or in-simulator driver behavior accompanied by model analysis is suggested to improve the capability of the DVM to model these effects.

More Flexible Model for Curve Cutting

The current model for curve cutting is limited to cutting to the inside of the curve and is applicable only to curves of constant radius. Consideration of the trailer wheels as well as the cab wheels would provide a basis for allowing trucks to track to the outside of a curve. Extension to compound curves would likely require a substantial modification of the model for curve cutting.

Effects of Driver Eye Height and Grade Differences on Curvature Estimation

The perspective view of a horizontal curve is influenced both by the height of the driver's eye above the road and difference in grade between the approach tangent and the curve. A study of on-road and/or in-simulator driver behavior is suggested to quantify the extent to which such perceptual differences influence the manner in which drivers approach and negotiate curves, accompanied by model development to adequately reflect such effects in the DVM.

Driver Expectation

The element of surprise cannot be programmed into the DVM. That is, violation of driver expectancy per se is not something that the DVM will flag. Therefore, the flags that were generated in testing the scenarios were potentially influenced more by the characteristics that make up an aggressive driver (e.g., waiting until the last possible moment to decelerate, driving fast through curves) than by the alignment itself. Future data collection and modeling efforts for the DVM should seek to add a parameter that allows driver expectation to be varied.

ADDITIONAL USER INTERFACE ENHANCEMENTS

Because the enhancements below were not deemed critical to the central goal of developing the DVM, implementation of these enhancements was not undertaken and is recommended for future model development.

Enhance the DVM output information so that it better conforms to end-user needs.

DVM users have suggested a number of improvements in output presentation and format. Specifications for realizing these improvements are summarized in Table 13. Accompanying each specification are suggestions related to its implementation; these suggestions are based on comments provided by the participants in a URA. Each of these specifications may be implemented by the FHWA as they deem appropriate.

Table 13. Initial list of DVM output improvements.

Specification	Suggestions related to implementation.
Provide the option of specifying either dynamic or structured stationing for the critical alerts table.	• Provide common stationing ranges between alternatives. • Provide the ability to export the output into a spreadsheet in order to make comparisons. • Include a tie-in with the plans to allow the user to identify the specific segments in order to compare different segments or geometric elements. • Allocate stationing by horizontal alignment element (i.e., tangent/ curve/tangent/curve).
Add a critical event threshold value or flag points at which thresholds are exceeded in the MOE graph to make identifying problem areas easier.	• Show flags where critical values are exceeded. • Include numerical values of the peaks and stations where these problems occur.
Provide more control over the format (e.g., scale options, graph sequence, etc.) of the MOE graph.	• Allow user-defined elements to be added/removed from the graph (e.g., provide capability to isolate important areas of the graph). • Provide the ability to order the placement of the individual elements (e.g., speed line, lateral acceleration, friction ratio, etc.). • Provide the ability choose the units for the graph. • Provide the ability to adjust the scale of the plot. • Provide an output table containing the raw data to enable additional graphs to be created by the user. • Allow users to customize their own reports and to combine elements from different reports. • Provide separate graph option as output.
Provide the ability to directly add labels, arrows, etc. to the plan-view graph.	• Elements that the user should have the option to display on the plan-view graph may include but are not limited to the following: o Stationing. o Point of curvature (PC), point of tangency (PT), and other key points of reference. o Vehicle path and how far it exceeds lane boundaries. o Curve radius values. o Side-by-side comparison of two different alternatives. o Design speed line. o Running speed line.
Provide the ability to indicate or display the critical alert warnings associated with flagged segments of the plan-view graph.	• Provide text labels that describe the underlying safety issue for each color designation of yellow and red. One possible solution is to provide the graph in dynamic form such that when the user runs the cursor over the section, the program will provide the pertinent information describing the cause of the safety issue. • Indicate severity when there is a combination of factors. • Provide the total length of yellow and red areas.

Table 13. Initial list of DVM output improvements. (Continued)

Specification	Suggestions related to implementation.
Provide the ability to align/tile the plan-view graph with horizontal and/or vertical views of the highway data set to get a clearer view of the stationing or highway features.	• Add (or provide the option to add) stationing to plan view. • Show PC, PT, and other key points of reference. • Align horizontal and vertical views, one above the other to provide a link between the stationing of each view. • Show vertical grid lines to aid in visual alignment. • Provide a side-by-side comparison of two different alternatives.
Only show the alert flags on the appropriate side of the highway based on the direction of travel.	• Alternatively, show alerts for the different travel directions simultaneously on the same graph but with some differentiating feature (e.g., color) for each direction of travel.
Provide the ability to auto-generate MOE graphs from the Additional Files information.	• Note: Participants indicated a high likelihood that they would use comparison information if the DVM provided the capability to automatically produce graphs internally. However, given the high level of response for the capability to export data to external software, the lack of automation does not seem to be a barrier for using this information for comparison purposes.
Provide an additional simplified version of the Additional Files that contains only MOE-related information and that has a more user-friendly format.	• Provide the option to display output data either as tables/numbers or graphically. • Provide the option to choose which MOE-related information to display.

Develop new Measures of Effectiveness (MOEs) based on degree of speed change and available SD.

Additional MOEs were suggested by the respondents to the URA conducted in task A.2. Two of these suggestions are addressed here: providing alert levels related to available SD and to speed changes associated with horizontal curves.

As discussed below, the DVM currently includes alerts for critical variables that are computed from ensemble statistics obtained from multiple trials. These alerts are associated with predicted probabilities of exceeding some criterion value, where only a single criterion value is associated with a particular variable (e.g., the probability that the vehicle lateral path exceeds the lane boundary).

To be consistent with the treatment of speed changes used in the DCM, the proposed alerts for speed change will involve two criterion values that define three ranges of predicted speed differences. In this case, the philosophy of predicting the probability of an out-of-bounds situation does not readily apply, and we introduce the notion of basing alert levels on the results of a single simulation trial or the ensemble mean of multiple trials. As we show below, alerts for some of the critical variables can be defined for both deterministic and statistical analysis.

Statistical Alerts

Statistical alerts are currently provided for path error, X and Y skid indices, and rollover index. Computation of an additional statistical alert for SD is proposed.

The SD requirement predicted by the DVM will in general differ from SD requirement specified by the "Green Book"[(8)] because the DVM is a dynamic model that predicts an instantaneous vehicle speed that in general is influenced both by highway geometry and assumed driver characteristics. The values for velocity used in computing the required SD in the "Green Book"[(8)] are based on the assumed design speed of the highway—a static variable.

The suggested procedure for computing SD alert levels is as follows:

1. Perform a multiple-trial simulation in which representative values are assigned to the noise processes associated with the perception of variables relevant to vehicle control. A simulation involving 30 to 40 trials is recommended for stable statistical results. For each trial, record the time histories of the available SD (currently computed in the DVM) and the required SD.

2. Upon the termination of the simulation trials, perform an ensemble analysis of the recording of instantaneous SD to compute, at regular station intervals, mean and standard deviation of available SD. Also compute the ensemble mean of the required SD.

3. On the assumption that the available SD has a Gaussian distribution, compute the probability that the available SD exceeds the instantaneous required SD.

4. Define an appropriate alert level for the station at which the following transitions occur:

   - Red alert if the probability of insufficient SD equals or exceeds 1%.

   - Yellow alert if the probability transitions into the range of greater 0.1 % but less than 1%.

   - Green alert if the probability falls below 0.1%.

These probability criteria are not theoretically based but were selected by the developers to provide a framework for conveying relative risk.

The SD alert levels can be included as an additional column in the tabular presentation of alert levels as shown in Table 14 for the four current levels. The max alert level should then indicate the maximum alert level of the five component alerts.

Table 14. Sample presentation of alert levels.

Max Alert Levels of Critical Variables (in the direction of increasing stations)						
Station		Max Alert	Lane Position	Friction Ratio X	Friction Ratio Y	Roll Over Index
From	To					
38	606	Green	Green	Green	Green	Green
606	608	Yellow	Green	Green	Yellow	Green
608	614	Red	Green	Green	Red	Green
614	616	Yellow	Green	Green	Yellow	Green
616	684	Green	Green	Green	Green	Green
684	686	Yellow	Green	Green	Yellow	Green
686	694	Red	Green	Green	Red	Green
694	698	Yellow	Green	Green	Yellow	Green
698	1142	Green	Green	Green	Green	Green

Deterministic Alerts

The DCM defines the following alert levels for speed decreases (in meters) associated with horizontal curves:

Green alert: $V_{diff} \leq 10.0$

Yellow alert: $10.0 < V_{diff} \leq 20.0$

Red alert: $20.0 < V_{diff}$

where

V_{diff} is the speed reduction.

The same definitions are recommended for the DVM.

The table of deterministic alerts should also include alerts related to lane position and SD. For the lane position alert, the instantaneous lane position is tested against the criterion value (default is lane boundary), a red alert is associated with transitioning outside the criterion value, and a green alert for transitioning into the lane. The instantaneous lane position is used in the calculation for a single-trial simulation; the ensemble mean of lane position is used for a multi-trial simulation. Similarly, red and green alerts are associated with the SD becoming insufficient or sufficient. Deterministic yellow alerts are not defined for either lane position or SD.

Add the ability to compare time histories from multiple model runs on the same graph.

At present, time histories from multiple model runs can be compared on the same graph only by using software (such as Excel) that operate on the output data files created by the DVM. Over half the participants in the URA conducted in task A.2 indicated they would have a use for being able to make such comparisons within the DVM environment. Table 15 lists specifications for providing comparisons of the output of multiple model runs from within the IHSDM environment. Comparison Mode Specifications lists the recommended format of the comparison outputs. Recommended Features Specifications describes some desirable features that may be incorporated to improve the utility of the output.

Table 15. Specifications for providing output comparisons.

Specifications	Description/Notes
Comparison Mode Specifications	
Overlapping graphs	Graphs from two or more trial runs are displayed directly on top of each other. In this mode, the output from one trial should be discriminable from that of another by color, line thickness, line type (e.g., dotted versus solid) or some other means.
Stacked graphs	Graphs from two or more trial runs are displayed one above another. In this mode, the user would find an alignment tool (e.g., vertical gridlines, dynamic vertical line that follows the mouse cursor, etc.) to be useful in determining related values from each graph.
Interlaced graphs	A graph that is generated from two or more trial runs and is grouped by parameter, with groupings stacked one above another. In this mode, each parameter that is common to between trial runs is displayed in a group, thereby facilitating close examination of differences between runs.
Tabular comparisons	The DVM should continue to provide data exportation capability to allow the user to develop custom graphs or use the data in external software applications.
Recommended Features Specifications	
Specify trials to be compared.	May be trials from the same multi-trial simulation or from different simulations.
Adjust scale factors to equilibrate time or distance scaling between graphs of two or more runs.	To facilitate a comparison between two or more trial runs, each common parameter must be scaled so that stations align between trials.
Provide the user with the ability to select parameters of interest	This feature will allow the user to streamline the output and provide the simplest useful representation of the data.
Provide the user with the ability to determine the order and placement of the parameters to be displayed.	In order to more easily compare values, users may wish to choose the order in which to display the parameters of interest. Similarly, users may desire to choose the order in which to display the results of each trial run.
Include legend or other identifying information to indicate which graph corresponds to each run.	Each graph must be clearly labeled to identify its associated run. For overlapping graphs and interlaced graphs, elements must be distinguishable not only by run but also by parameter.
Provide the user with the ability to highlight parameters of greater importance or priority	Users may wish to highlight certain parameters within a larger parameter set to facilitate flexibility in presentation of the data.

RECOMMENDATIONS FOR USING THE DVM

Despite the constraints and limitations associated with the current version of the DVM, the DVM does indeed provide some real value to highway designers. If its applicability can be expanded to other roadway types (e.g., nonrural roadways) and driving conditions (e.g., multiple vehicles on the roadway, bad weather), it can become more broadly valuable. The DVM has already been used by a small number of highway designers to evaluate new rural road designs and has produced some useful and interesting results. Given its limitations, it is perhaps most useful (in its current form) as a tool for identifying those portions of a candidate roadway that are clearly unsafe and should perhaps be re-designed or subjected to further analysis.

FUTURE R&D RECOMMENDATIONS FOR THE DVM

Key recommendations for future DVM R&D are listed above. Additional enhancements to the DVM that we recommend include the addition of:

- Other vehicles into the driving scenario.
- Multi-lane highways.
- Traffic signals.
- Intersections.
- Multiple driver tasks.

A key recommended enhancement to the DVM is a full Java implementation that eliminates Visual Basic components.

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APPENDIX A – DRIVER/VEHICLE CONFIGURATION PARAMETERS

Configuration	Vehicle	Driver Type	Cuts Curve?
Deterministic nominal-center/Taurus	Passenger car	Nominal	N
Deterministic nominal-cutcurve/Taurus	Passenger car	Nominal	Y
Deterministic aggressive-center/Taurus	Passenger car	Aggressive	N
Deterministic aggressive-cutcurve/Taurus	Passenger car	Aggressive	Y
Deterministic nominal-center/truck	Truck	Nominal	N
Deterministic nominal-cutcurve/truck	Truck	Nominal	Y
Deterministic aggressive-center/truck	Truck	Aggressive	N
Deterministic aggressive-cutcurve/truck	Truck	Aggressive	Y
Stochastic nominal-center/Taurus	Passenger car	Nominal	N
Stochastic nominal-cutcurve/Taurus	Passenger car	Nominal	Y
Stochastic aggressive-center/Taurus	Passenger car	Aggressive	N
Stochastic aggressive-cutcurve/Taurus	Passenger car	Aggressive	Y
Stochastic nominal-center/truck	Truck	Nominal	N
Stochastic nominal-cutcurve/truck	Truck	Nominal	Y
Stochastic aggressive-center/truck	Truck	Aggressive	N
Stochastic aggressive-cutcurve/truck	Truck	Aggressive	Y

where:

“Nominal” approximates the average response characteristics of the test drivers.

“Aggressive” approximates the 85th percentile driver.

Not cutting the curve means the driver attempts to maintain lane center in horizontal curves.

Cutting the curve means the driver tracks to the inside of horizontal curves.

Recycled
Recyclable

HRDS-02/11-07(WEB)E