CHARACTERIZATION OF A SINGLE-VEHICLE ROAD DEPARTURE AVOIDANCE MANEUVER

Peter G. Martin, August L. Burgett, Gowri Srinivasan
National Highway Traffic Safety Administration
United States of America
Paper No. 308

ABSTRACT

This paper demonstrates how a driver's performance in a single-vehicle road departure avoidance maneuver may be characterized using mathematical expressions. Nine single-valued covariates are needed to fulfill the expressions: five to describe the pre-maneuver vehicle state (speed, heading angle, edge distance, road curvature, and curve entry distance) and four to describe the driver response (brake application time, deceleration level, steering input time, and steering angle). A procedure to find the best set of covariate values is demonstrated using a trial from a series of test track experiments in which subjects maneuvered along a Jersey barrier. The procedure provides a high level of conformity between the actual vehicle path with respect to the barrier and the path derived from the nine covariates. Thus, the entire avoidance maneuver may be faithfully described by a set of mathematical expressions. Subsequently, each of the thousand-plus test track trials is characterized by a single, nine-covariate data record (instead of several time-histories made up of thousands of records, one for each time point). Ultimately, such a reduction in data benefits the development of an in-vehicle crash warning system. By structuring the avoidance maneuvers in a record-level dataset, warning system alternatives may be investigated directly by applying traditional statistical analyses on a large collection of records. The paper discusses extensions of the method to the theoretical possibility of continuously estimating the nine parameters in real time as part of a collision avoidance driver assistance system.

BACKGROUND

In a single-vehicle road departure avoidance maneuver, a driver's performance may be based on four responses: two related to braking (the time of brake application and the level of deceleration) and two related to steering (the timing of steering input and level of lateral acceleration). Many road departures may be avoided through the use of some sort of advanced crash warning system that signals a driver to brake or steer (Pomerleau and Evanston, 1999). For such a system to be effective, it must be equal to all emergencies without signaling false alarms such that drivers will consider the system to be an overbearing nuisance. Therefore, the warning system must discriminate between an impending crash and one that is likely to be avoided. To do so, it must evaluate the likelihood of an impending road departure using some mathematical relationship between instrument readings (presumably the system monitors several on-board instruments – speed, acceleration, range, etc.) and the probability of crashing. At the appropriate instant, the system will then signal the driver to take action.

As a precursor to developing an effective warning system, data from real driving experiences are needed that will place the four driver responses in their proper perspectives. In other words, a mathematical relationship is needed in which the outcome of an avoidance maneuver (crash or no crash) may be written as a function of the four responses. This relationship may be applied to a population of actual avoidance maneuvers so that driver tendencies under different scenarios may be understood. Ultimately, a database of avoidance maneuvers may be compiled so that the probability of crashing under any given scenario may be found.

Data for real driving experiences – or test trials – may come from naturalistic driving tests, test track experiments, and driving simulator studies. No matter what the data source, it is assumed that each test trial is recorded by a set of time-histories sampled from test instrumentation. The challenge is to create simple mathematical functions of time that match all aspects of the actual maneuver as measured by the test instrumentation (such as speed, deceleration, distance to the road edge, and lateral deceleration).

These functions are presented herein, along with a methodology that demonstrates how an actual road departure event may be fully characterized by a set of nine covariates that correspond to the four driver responses, plus five initial conditions. In this manner, the several time-histories that describe the event are reduced to a set of nine constants. Subsequently, a database of events may be assembled from various sources so that driver behavior may be evaluated evenhandedly. This database may be used to develop an effective warning system by discerning the appropriate times to issue warnings.

METHODS

Martin and Burgett (2001) show how a simplified mathematical expression may be formed to accurately characterize an impending "rear-end" crash. The objective of this paper is to develop a similar expression for an impending road departure. Once accomplished, the terms that make up such an expression may provide insight into the circumstances associated with successful avoidance maneuvers. For example, Burgett and Gunderson (2001) define several terms used to derive a two-dimensional theoretical boundary that separates a "crash response" from a "no-crash response" under an impending road departure scenario. These terms include a driver's applied steering and the lateral acceleration it produces, road curvature, vehicle speed, approach angle, and the distance to the road edge.

When road departure avoidance maneuvers involve both steering and braking, a four-dimensional boundary is needed. Separate terms are needed for the times at which steering begins and the brakes are applied (t_s and t_b). Also needed are separate terms for the levels of braking deceleration, *d*, and lateral acceleration (which is a function of the vehicle turning radius, R_v, applied by the driver). As such, a proposed mathematical characterization of a road departure avoidance maneuver is based on the following presumptions:

a. At the beginning of the event, the vehicle is positioned at a drift angle, θ_o, with respect to the road and the vehicle is traveling straight (and not turning). This drift angle is assumed to remain constant until time t_s (the steering time). At t_s, the driver initiates a turn of a constant radius R_v through the remainder of the event.

b. At the beginning of the event, the vehicle is at a straight-ahead distance of R_o from the road edge and is traveling at velocity V_o. If the road is curved at the projected point of departure, then R_1 is the distance from the vehicle to the entry point into the curved portion of the road. (If the vehicle has already entered the road curve at the beginning of the event, then R_1 is negative-valued.)

c. The driver begins to decelerate at time t_b (the braking time) at a constant deceleration level, *d*, through the remainder of the event. Prior to t_b, the vehicle velocity travels at a constant level, V_o.

d. The road is perfectly straight up to the point where the curve begins. The curved portion of the road may be characterized as having a constant radius of curvature, R_{curve}, for the duration of the event.

Therefore, a set of nine single-valued covariates (see Table 1) is needed to describe the trajectory of a vehicle during an avoidance maneuver: the four covariates that describe the driver response during the maneuver (t_s, R_v, t_b, and *d*) and five other state covariates (initial conditions) used to characterize the scenario.

Table 1. The nine single-valued covariates that may be used to fully describe a road departure avoidance maneuver.

Cov.	Covariate Type	Comment
t_s	Driver reaction	Time of steering application.
R_v	Driver reaction	Applied steering turn radius.
t_b	Driver reaction	Time of brake application.
d	Driver reaction	Braking deceleration.
R_o	Initial state	Initial lead distance to road edge.
R_1	Initial state	Initial lead distance to road curve.
R_{curve}	Initial state	Radius of road curve.
V_o	Initial state	Initial velocity.
θ_o	Initial state	Initial approach angle.

In an actual road departure maneuver, the presumptions (a. through d. above) are always violated to some degree. For example, measures of braking deceleration are never constant in a test, so a "best approximation" strategy must be used to select the appropriate value of *d* that characterizes the performance of the driver best. Such a strategy is described herein. It uses an optimization procedure aimed at finding values for all nine covariates such that a theoretical plot of the vehicle trajectory provides the best fit to the actual trajectory.

The theoretical trajectory of the vehicle with respect to the road may be laid out in an *x-y* coordinate system as shown in Fig. 1. The origin of the coordinate system (0,0) is located at the projected road departure point, Point A. Eight other useful points are also shown in Fig. 1. The significance of each of these points is provided in Table 2 along with their *x-y* coordinates as functions of the nine covariates.

The goal is determine values of the nine covariates [t_s, R_v, t_b, d, R_o, R_1, R_{curve}, V_o, θ_o] such that the theoretical trajectory overlaps the actual (or experimental) trajectory. (In the foregoing equations, the superscripts "Theo" and "Exp" are used to differentiate between theoretical and experimental values.) The goal is accomplished by first obtaining time-histories of the actual vehicle *x-y* coordinates (x^{Exp}, y^{Exp}) throughout the event. Then, expressions for the theoretical *x-y* coordinates of the vehicle (x^{Theo}, y^{Theo}) are written in terms of the nine covariates and time, t. Finally, values for the nine covariates that provide the best match between theoretical and experimental coordinates are determined via nonlinear regression. The following discussion explains the entire process more fully.

Fitting the theoretical trajectory. A mathematical expression that describes the theoretical vehicle trajectory contains both steering and braking covariates. A multi-step "fit" procedure is used to determine values of the nine covariates such that the theoretical trajectory matches the experimental one. In the first step, values for the three covariates associated with braking may be determined independently of the steering-related covariates. In subsequent steps, the fitted braking covariates are used to find the remaining covariates. The steps are described below.

Defining actual x-y coordinates relative to Point A. Given data on an actual road departure avoidance maneuver, the trajectory of the experimental vehicle may be plotted by constructing a diagram like the one in Fig. 1 in which Point A is defined as the origin. It is assumed that the road geometry and time-histories of the vehicle coordinates (x^{Exp}(t), y^{Exp}(t)) with respect to Point A are available from some sort of test instrumentation. For simulator studies, this information is usually available via system programming software. In field operational tests, the information may be deduced by manipulating data collected by some type of on-board vehicle instrumentation. For example, the test vehicle may be equipped with a system that makes use of Global Position Satellites (GPS) which tracks the coordinates of the vehicle in time. It could also have knowledge of the coordinates and geometry of the road edge, which is theoretically available from a Geographic Informational System (GIS) map. Such a GPS/GIS-based system could continually evaluate the vehicle position with respect to the road edge so that a plot of an avoidance maneuver like the diagram in Fig. 1 could be constructed.

Event starting point and end point. Obtaining a good trajectory fit depends on the way in which the beginning and ending of the event are defined. The critical maneuver – and the events leading up to it – lasts only a few seconds. When fitting the nine characterization constants to experimental data, only data from the critical event itself (and not pre- or post-event "normal driving" data) are desired. Otherwise, the fit may be lacking: since it is an averaging procedure over the entire trajectory, an event that is started too soon may sacrifice a good fit around the critical maneuvering portion of the trajectory in favor of a good fit around the non-critical "normal driving" portion. This would likely produce a fitted trajectory that underestimates the severity of the avoidance action (i.e., lateral acceleration estimates will be too low). Therefore, heuristics are used to mark the beginning and ending of the steering maneuver. These rules of thumb provide consistency and while capturing the essence of the maneuver.

Refer to the trajectory overlay (Fig. 1) with the origin defined as Point A. The position of the vehicle at time t=0 marks the start of the event, or entry into a "danger plane". This "danger plane" entry point is located along the *x*-axis that begins somewhere to the left of the projected road departure point and signifies a heightened risk of an impending road departure. When the vehicle first enters the danger plane, its *x*-coordinate is equal to $x = B_x$ and it marks the start of the event, time t=0. A typical driver reaction time from conflict recognition to steering or braking initiation is about one second. On the other hand, drivers who respond too late and depart the road certain entered the danger plane well beforehand. For these drivers, entry into the danger plane is arbitrarily defined to occur when x = -45 m, which seems to be a reasonable distance for vehicle speeds of 35 to 65 mph. Therefore, the beginning of the event is assumed to occur one second prior to the time when the steering is initiated or when B_x = -45 m, whichever occurs first.

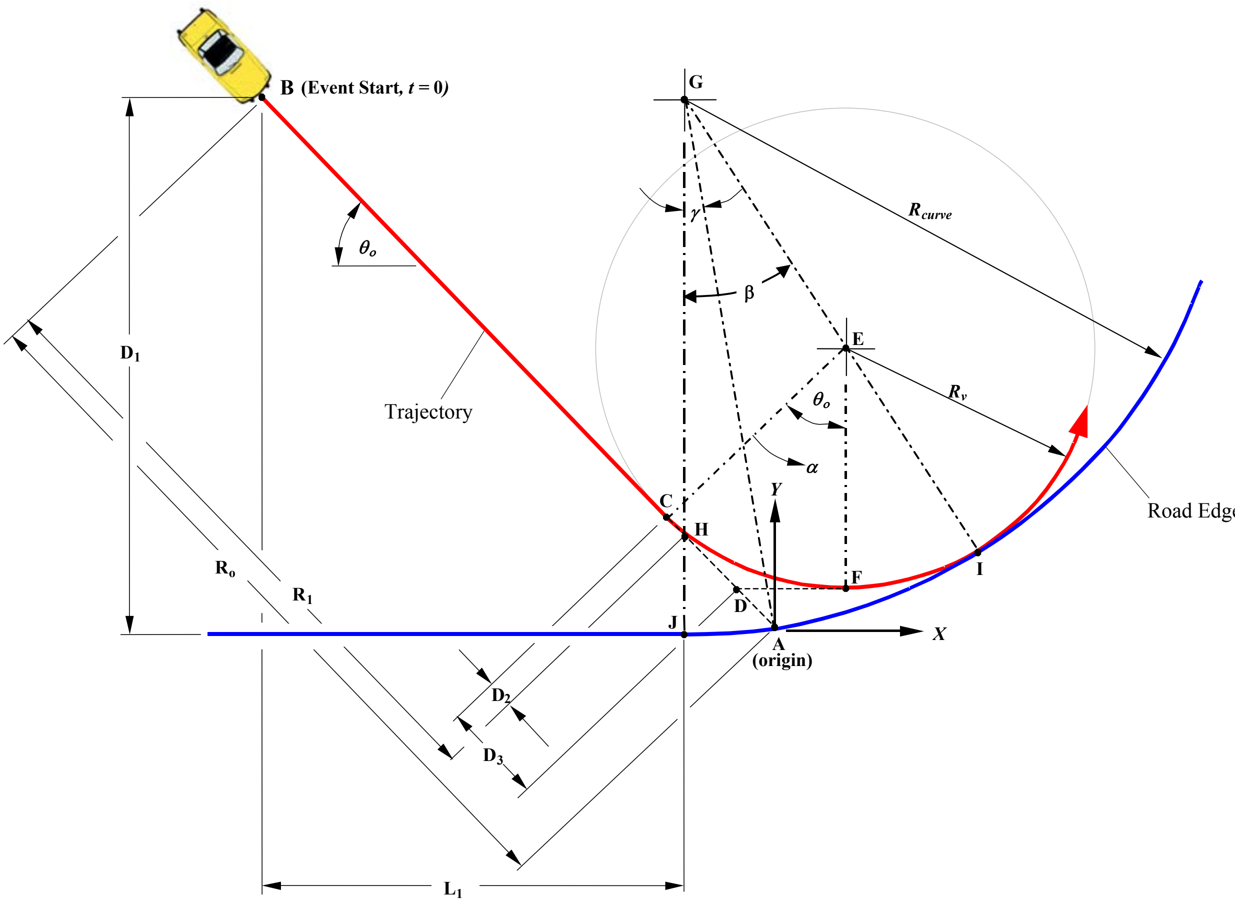

Figure 1. Vehicle trajectory for a road departure avoidance maneuver.

Table 2. Coordinates of reference points near and along theoretical vehicle trajectory.

Point	*x*-coordinate	*y*-coordinate	Comment
A	0	0	Origin; projected departure point.
B	$-R_o\mathrm{Cos}[\theta_o]$	$R_o\mathrm{Sin}[\theta_o]$	Event Start, t = 0.
C	$B_x + [V_o t_s - (d/2)\{Max(0,t_s\text{-}t_b)\}^2]\mathrm{Cos}[\theta_o]$	$B_y - [V_o t_s - (d/2)\{Max(0,t_s\text{-}t_b)\}^2]\mathrm{Sin}[\theta_o]$	Steering initiation, $t = t_s$.
E	$C_x + R_v \mathrm{Sin}[\theta_o]$	$F_y - R_v$	Origin of turning radius.
F	E_x	$C_y - R_v(1 - \mathrm{Cos}[\theta_o])$	Point of "minimum Y".
G	$- R_{curve} \mathrm{Sin}[\gamma]$	$R_{curve} \mathrm{Cos}[\gamma]$	Origin of road curve.
H	G_x	$- G_x \mathrm{Tan}[\theta_o]$	Road curve entry point
I	$E_x + R_v \mathrm{Sin}[\beta]$	$E_y - R_v \mathrm{Cos}[\beta]$	Point of closest approach.
J	G_x	$R_{curve} (\mathrm{Cos}[\gamma] - 1)$	Start of road curvature

Table 3. Measurements identified in Fig. 1 that are used to determine vehicle trajectory.

Measure	Function of Nine Parameters	Comment
L_1	$R_1 \, Sin[\theta_o]$	Initial lead distance to road curve.
D_1	$R_o Sin[\theta_o] + R_{curve} \, (Cos[\gamma] - 1)$	Initial lateral distance from road edge.
D_2	$R_1 - (V_o \, t_s - (d/2)[Max(0,t_s\text{-}t_b)]^2 \,)$	Projected distance to road curve at time t_s.
γ	$ArcSin[Cos[\theta_o] \, (R_o - R_1)/R_{curve}]$	Subtended road curve angle at origin.
β	$ArcTan[\, (E_x - J_x)/(R_{curve} - (E_y - J_y)) \,]$	Subtended angle at closest approach point.

The ending of the event is also defined rather arbitrarily. It is taken as one second after the time at which the experimental lateral deceleration reaches its maximum, t @ a_{Lmax}, where:

$$a_{Lmax} = V^2 / R_v \qquad [1]$$

This may seem counterintuitive because in many cases the vehicle is still approaching the edge of the road at t @ a_{Lmax}. It may seem that the time when the range rate becomes positive (or when the vehicle begins to diverge from the road edge) would be a better choice for the ending point. The rationale for using (t @ a_{Lmax} + 1 sec) is that peak deceleration usually occurs shortly before the driver perceives that the conflict is under control even though the car is still headed towards the road edge. Afterwards, the driver may take a more gradual course towards the road edge, drive alongside of it, and then eventually veer away. Since the characterization procedure is aimed at characterizing "conflicts", including data much further beyond t @ a_{Lmax} would generally lower the angular deceleration estimates and lessen the characterized severity of the "conflict".

Once the vehicle enters the pre-defined "danger plane", a reference coordinate system is defined, (including an origin at Point A), and initial conditions V_o, R_o, R_1, and θ_o may be computed. For the remainder of the event, the global vehicle and road coordinates must be transformed to this coordinate system, which must be oriented in a manner consistent with the one laid out in Fig. 1 (i.e., the *x*-axis is parallel to the straight portion of the road, and the origin corresponds with the projected point of road departure).

Fitting braking covariates V_o, t_b, and d. Once the beginning and ending of the critical avoidance maneuver have been defined, the theoretical braking covariates may be estimated. It is assumed that an experimental velocity time-history – recorded by some type of vehicle instrumentation system – is available for the duration of the event. This velocity time-history alone – and not measurements of steering, GIS, or any other data – are used to determine the theoretical best-fit values of d, V_o, and t_b. These values are found by minimizing the difference between the experimental and theoretical velocity time-histories over the duration of the critical avoidance maneuver:

$$\Sigma \, (V(t)^{Theo} - V(t)^{Exp})^2 \Rightarrow 0 \qquad [2]$$

where the theoretical time-history is expressed as:

$$V(t)^{Theo} = V_o - (d/2) \, \{Max[0, t - t_b]\}^2 \qquad [3]$$

Expressions for the theoretical *x*-*y* coordinates. The next step involves writing expressions for the theoretical vehicle coordinates, $x^{Theo}(t)$, $y^{Theo}(t)$. First, the theoretical *x*-coordinate is set to coincide with the experimental one at every timepoint. Therefore, no distinction is made in the foregoing equation development between x^{Theo} and x^{Exp}:

$$x^{Theo}(t) = x^{Exp}(t) = x(t) \qquad [4]$$

Secondly, five sets of expressions are written for $x(t)$ and $y^{Theo}(t)$ based on the amount of time which has passed since the vehicle has entered the "danger plane". At each timepoint, only one set applies. The appropriate set depends upon the instantaneous time relative to both t_b and t_s. Two of the sets represent the time before steering is initiated, while the other three represent post-steering times. For the three post-steering cases, the *x*-coordinate is a function of α, the instantaneous angle through which the vehicle has passed since time $t=t_s$ as shown in Fig. 2. As such, the *x*-coordinate for the three post-steering cases may be expressed as a function of α (subscripts of x denote case numbers):

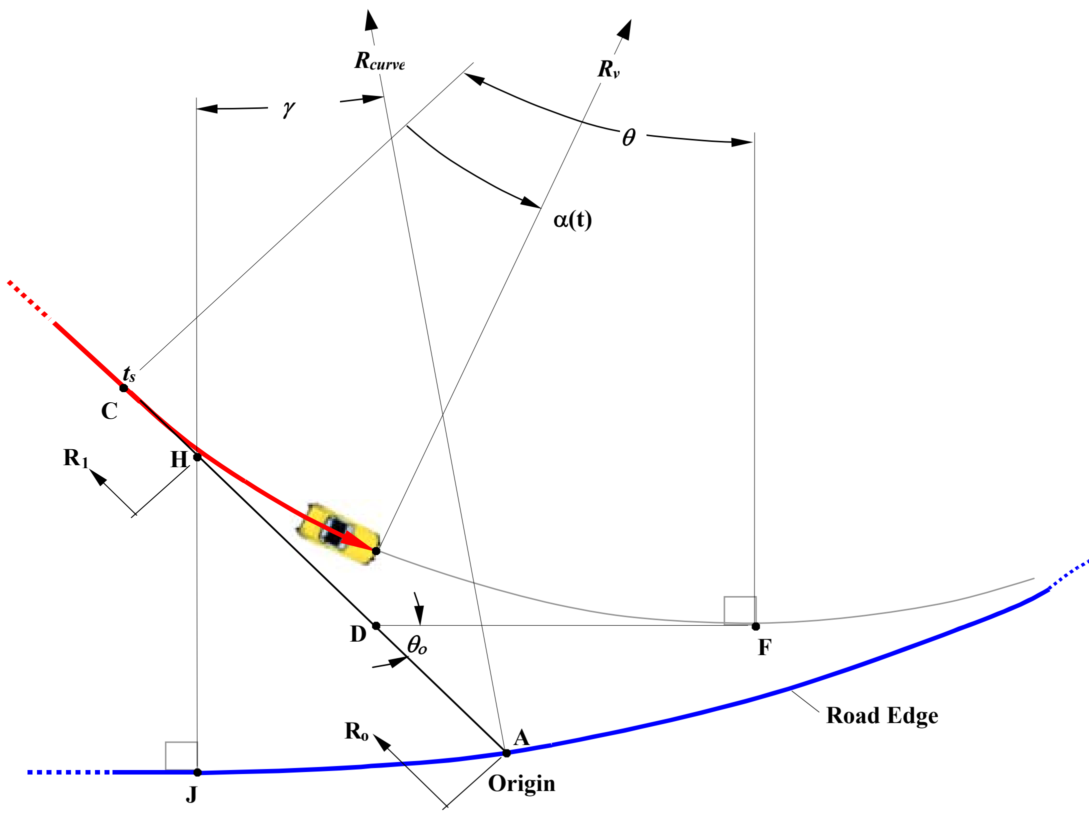

Figure 2. Position of the vehicle once steering has been initiated. Ref: Cases 3 - 5.

$$x_{3,4,5}(t) = C_x + R_v\mathrm{Sin}(\theta_o) - R_v\mathrm{Sin}[\theta_o - \alpha(t)] \quad [5]$$

This expression may be solved for α(t):

$$\alpha(t) = \theta_o + \mathrm{ArcSin}[(x(t) - C_x - R_v\mathrm{Sin}(\theta_o))/ R_v] \quad [6]$$

Note that:

$$\alpha(t) = \frac{[\text{Distance travelled since } t = t_s]}{R_v} \equiv \frac{D_{t_s} \to t}{R_v} \quad [7]$$

Therefore, the expression becomes:

$$D_{ts\to t}(t) = R_v\, \theta_o + R_v\mathrm{ArcSin}[(x(t) - C_x - R_v\mathrm{Sin}(\theta_o))/R_v] \quad [8]$$

The distance travelled since time t = t_s, $D_{ts\to t}(t)$, depends on which case applies. The flowchart in Fig. 3 may be used to determine which case applies at any particular instant. An expression for the *x*-coordinate as a function of time, t, may be written for each case. Then, each case may be solved for time, t. Finally, an expression for the *y*-coordinate as a function of time, t, may be written for each of the five cases.

Case 1. $t < t_b$ and $t < t_s$. Neither steering nor braking has begun. Note: $D_{1:t_s\to t}(t) = \alpha(t) = 0$.

$$x_1(t) = B_x + V_o t\,\mathrm{Cos}(\theta_o) \quad [9]$$

$$t_1 = (x_1 - B_x)/(V_o\mathrm{Cos}(\theta_o)) \quad [10]$$

$$y_1^{Theo}(t) = B_y - V_o t_1 \mathrm{Sin}(\theta_o) \quad [11]$$

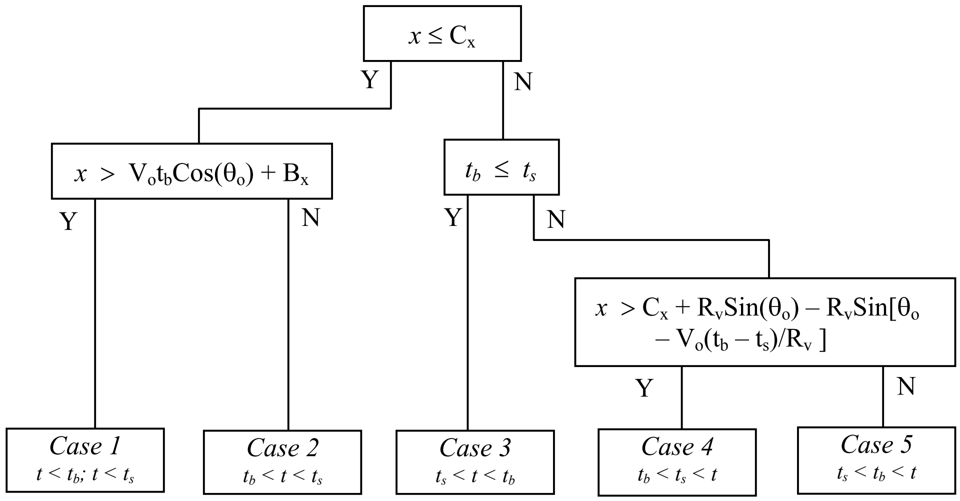

Figure 3. Flowchart to determine avoidance maneuver case type.

Case 2. $t_b < t < t_s$. Braking has begun, but not steering. Note: $D_{2:t_s \to t}(t) = \alpha(t) = 0$.

$$x_2(t) = B_x + [V_o t - (d/2)(t - t_b)^2\ ]Cos(\theta_o) \qquad [12]$$

This is a quadratic expression which may be solved for t by setting:

$$t_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \qquad [13]$$

where: $a = d/2$

$b = -(d\, t_b + V_o)$

$c = (x_2 - B_x)/Cos(\theta_o) + (d/2)t_b^2$

$$y_2^{Theo}(t) = B_y - [V_o t_2 - (d/2)(t_2 - t_b)^2\ ]Sin(\theta_o) \qquad [14]$$

Case 3. $t_s < t < t_b$. Steering has begun, but not braking.

$$\alpha_3(t) = D_{3:ts \to t}(t) / R_v \qquad [15]$$

$$D_{3:ts \to t}(t) = V_o(t - t_s) \qquad [16]$$

$$x_3(t) = C_x + D_{3:t \to t}(t) \qquad [17]$$

$$t_3 = t_s + (x_3 - C_x + V_o t_s)/V_o \qquad [18]$$

$$y_3^{Theo}(t) = E_y - R_v Cos(\alpha_3(t) - \theta_o) \qquad [19]$$

Case 4. $t_b < t_s < t$. Braking and steering have both begun, and braking began first.

$$\alpha_4(t) = D_{4:ts \to t}(t) / R_v \qquad [20]$$

$$D_{4:ts \to t}(t) = V_o(t - t_s) - (d/2)\ [(t - t_b)^2 - (t_s - t_b)^2] \qquad [21]$$

$$x_4(t) = C_x + D_{4:ts \to t}(t) \qquad [22]$$

$$t_4 = \frac{-b - \sqrt{b^2 - 4ac}}{2a} + t_s \qquad [23]$$

where: $a = d/2$

$b = -(d\, t_b + V_o)$

$c = R_v\theta_o + R_v ArcSin[(x_4 - C_x - R_v Sin(\theta_o))/R_v)] + V_o t_s - (d/2)t_s^2 + d\, t_s t_b$

$$y_4^{Theo}(t) = E_y - R_v Cos(\alpha_4(t) - \theta_o) \qquad [24]$$

Case 5. $t_s < t_b < t$. Braking and steering have both begun, and steering began first.

$$\alpha_5(t) = D_{5:ts \to t}(t) / R_v \qquad [25]$$

$$D_{5:ts \to t}(t) = V_o(t - t_s) - (d/2)(t - t_b)^2 \qquad [26]$$

$$x_5(t) = C_x + D_{5:ts \to t}(t) \qquad [27]$$

$$t_5 = \frac{-b - \sqrt{b^2 - 4ac}}{2a} + t_s \qquad [28]$$

where: $a = d/2$

$b = -(d\, t_b + V_o)$

$c = R_v\theta_o + R_v \mathrm{ArcSin}[(x_5 - C_x - R_v \mathrm{Sin}(\theta_o))/R_v)] + V_o t_s + (d/2)t_b^2$

$$y_5^{Theo}(t) = E_y - R_v \mathrm{Cos}(\alpha_5(t) - \theta_o) \qquad [29]$$

Regression procedure to find θ_o, t_s and R_v. Recall that R_o defines the event starting point. Therefore, the regression procedure is carried out by holding the initial distance measures (R_o, R_1, R_{curve}) and the Step 1 values (V_o, d, and t_b) constant, and varying the covariate values of θ_o, t_s and R_v until the difference between the theoretical and experimental *y*-coordinates is minimized. In other words, the regression procedure searches for optimum values of θ_o, t_s and R_v that minimize the difference of y^{Theo} and y^{Exp}, or:

$$\Sigma\, (y^{Theo} - y^{Exp})^2 \Rightarrow 0 \qquad [30]$$

A nonlinear regression procedure such as Marquardt's procedure (SAS, 2000) or Microsoft Excel's Solver function may be used to find the optimum values.

"Just Touch" Input Values for Steering. As shown in Fig. 1, Point I represents the vehicle's point of closest approach to the road edge. For most avoidance maneuvers, drivers maintain a safe distance from the road edge so that the vehicle trajectory and the road trajectory never intersect. (Such is the case in the forthcoming example of a real-world maneuver that is diagrammed in Fig. 5, where the closest distance between the car and the road edge is about 3 meters.) A last second steering time, t_s', that would have produced a "just touch" situation if all other driver inputs (the eight other components listed in Table 1) remain unchanged may be computed. Likewise, a wide-angle turn radius, R_v', that would have resulted in a "just touch" condition may be computed. Equation [31] expresses the relationship that must be satisfied under a "just touch" condition.

$$E_x - J_x + R_v \,\mathrm{Sin}\, \beta = R_{curve} \,\mathrm{Sin}\, \beta \qquad [31]$$

Theoretically, this expression may be expanded to include all the t_s and R_v terms. Then the last second braking may be found by solving the expression for t_s while holding all other terms unchanged. Similarly, the wide-angle turn radius may be found by solving the expression for R_v. Both expressions, however, are rather long, quite unwieldy, and are not given here. As an alternative, a non-linear routine such as Microsoft Excel's Solver program may be used to find the values by simply forming the equations for both sides of Eq. [31] and searching for values of t_s' (or R_v') such that the two sides are equal.

RESULTS

The optimization procedure is demonstrated on a typical trial run that was carried out recently on a test track at the Vehicle Research and Test Center (VRTC) in East Liberty, OH (Barickman et al, 2003). The VRTC test track was set up to examine the relationship between initial velocity (35 mph and 55 mph), approach angle (7 degrees, 5 degrees, and 3 degrees), and direction of approach (North and South) in an impending road departure scenario. Twenty-six subjects completed a total of 72 trials consisting of 6 trials per cell (approximately 1300 valid maneuvers).

At VRTC's test track, the road edge is perfectly straight, so two of the nine covariates, R_1 (initial lead distance to road curve) and R_{curve} (radius of the road curve) are known: $R_1 \rightarrow 0$ and $R_{curve} \rightarrow \infty$. The preceding methodology is used to determine the other seven covariates, and the results are plotted in Fig. 4 which compares the actual vehicle velocity with the theoretical velocity, and Fig. 5 which compares the trajectories. Furthermore, the "just touch" trajectory is shown for the VRTC trial in Fig. 6 for the last-second steer time. (A similar plot for a wide-turn radius is not shown.)

Note that "just touch" values for the braking inputs may also be computed by solving for a minimum deceleration, d′, and a last-second brake application time, t_b'. However, most steering maneuvers (including the one depicted in Fig. 5) rely less on braking and more on steering. For example, consider the Fig. 5 maneuver, which *does* include some amount of braking. If there had been no steering at all (but all other driver inputs were the same), a road departure would have occurred. Thus, the values of t_s' and R_v' represent limiting driver inputs for the "just touch" condition. On the other hand, if there had been no braking at all (but all other driver inputs were the same), it still would have been a successful avoidance maneuver, albeit one that comes slightly closer to the road edge. Thus, there are no complimentary d′ and t_b' values to represent a "just touch" situation. Since most departure maneuvers fall into this category, the t_s' and R_v' values strike much more interest.

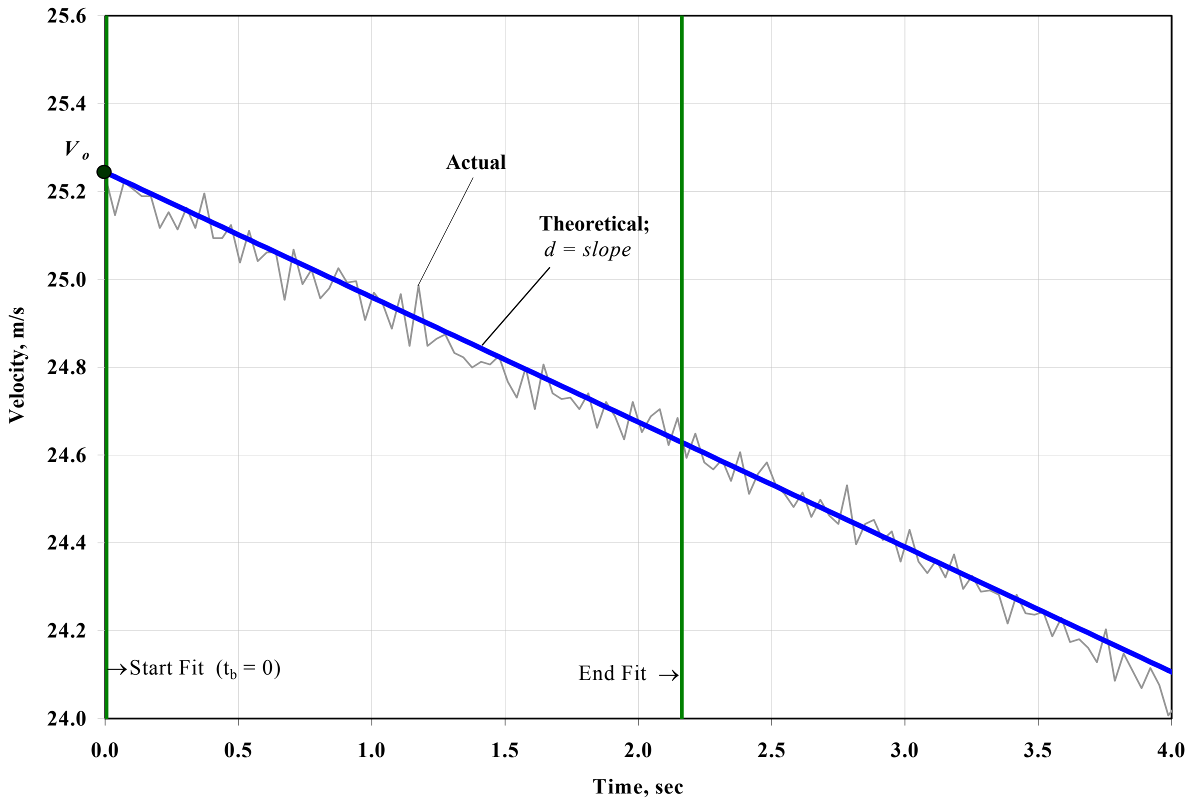

Figure 4. Actual vehicle velocity plotted against the theoretical one fitted by selecting appropriate values of V_o, *d*, and t_b.

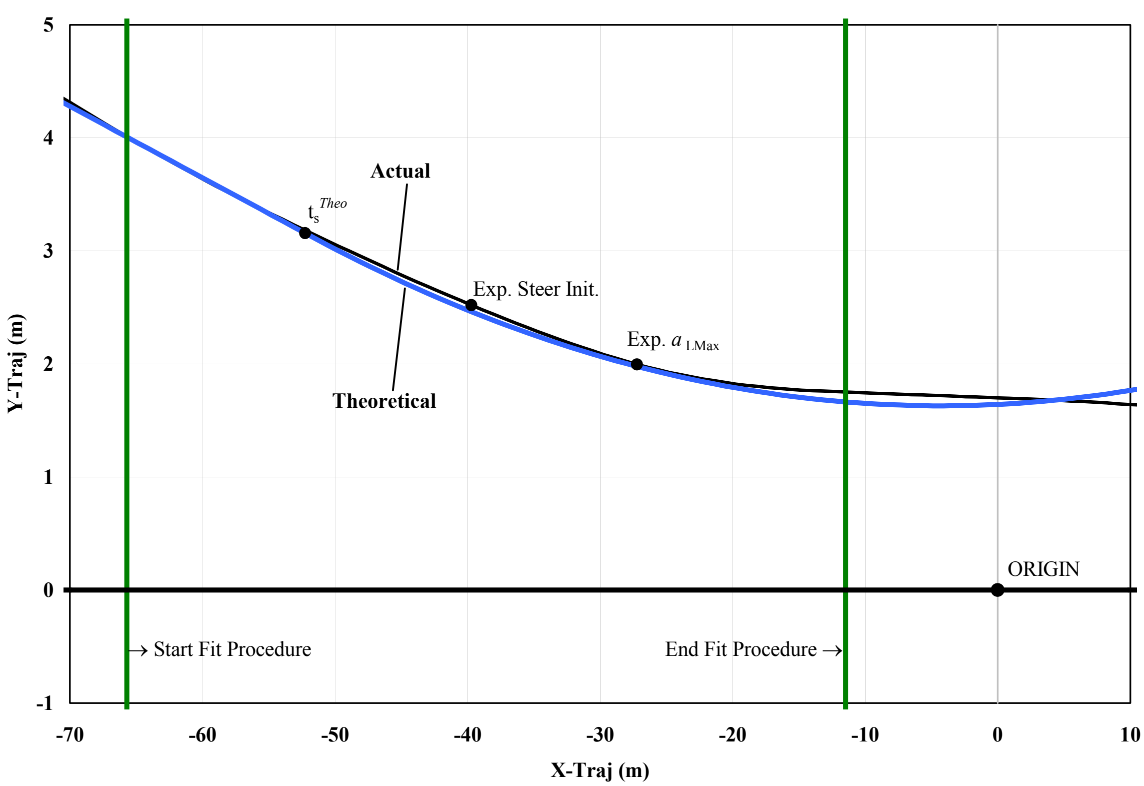

Figure 5. Actual vehicle trajectory plotted with the theoretical one fitted by selecting appropriate values of θ_o, R_v, and t_s.

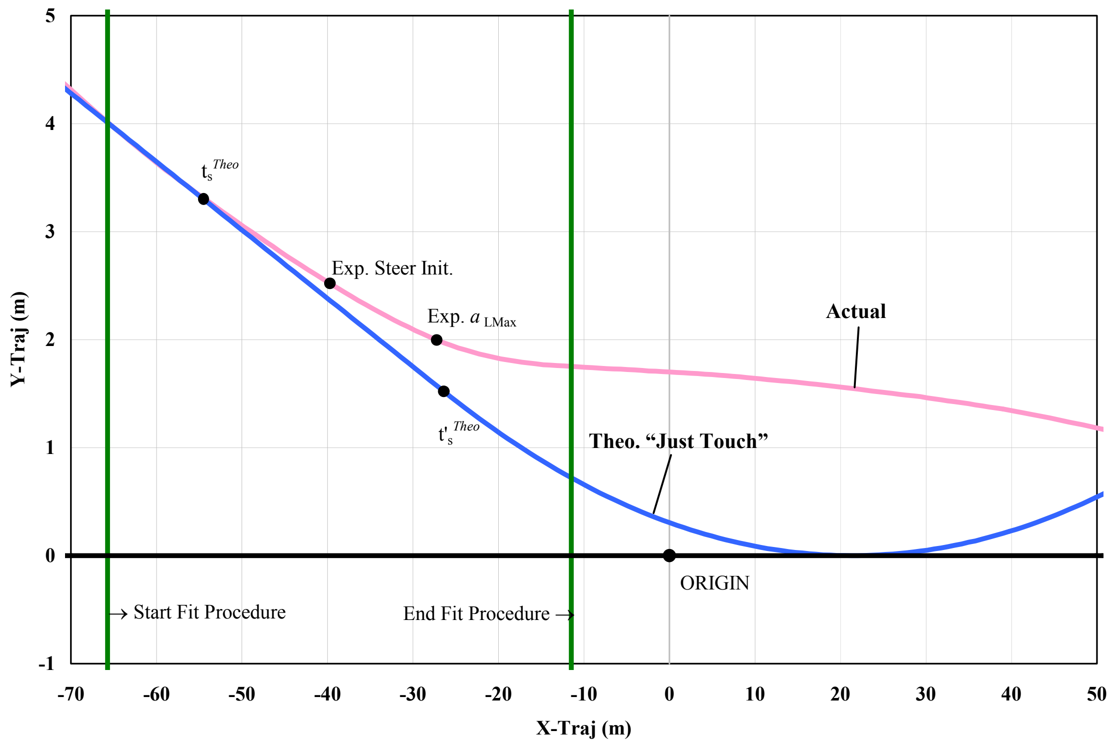

Figure 6. Actual vehicle trajectory plotted with the theoretical "just touch" one fitted by selecting an appropriate value of t_s' that is slightly greater than t_s.

Analysis of Driver Trends. The greatest benefit of the characterization method comes when an entire population of events has been characterized. Then, a statistical analysis may be carried out to gain insight into driver behavior trends useful in developing a crash avoidance system. To that end, 1300 sets of optimized covariates were determined for all the valid VRTC test trials (one for each avoidance maneuver). The relationship of vehicle speed versus the time to road departure (TRD) at steering is examined by comparing TRD distributions. (TRD represents the amount of time that would have elapsed between t_s and the time the vehicle departed from the road if the driver had not maneuvered to avoid the departure.) Figure 7 shows that TRD increases as vehicle speed increases. Given that a lower TRD reflects a more imminent danger, Fig. 7 indicates that drivers traveling faster may need to be warned sooner. Likewise, Fig. 8 shows that TRD decreases as the angle of approach, θ_o, increases, so drivers aimed at a greater approach angle may need an earlier warning signal.

The distributions shown in Figs. 7 and 8 are determined via kernel density estimation (SAS, 1999) in which a known density function is averaged across the observed data to create a smooth approximation. The figures also indicate that TRD follows an approximately log-normal distribution, another useful finding in characterizing driver response. Kernel density parameters are listed in Table 4.

Table 4. Kernel density distribution parameters determined via simple normal reference (SAS, 1999).

Type	Inclusive	n	Bandwidth
All cases	——	1335	0.1098
55 mph	+/- 3 mph	475	0.1236
35 mph	+/- 3 mph	829	0.1032
3 º	+/- 0.5º	323	0.1692
7 º	+/- 0.5º	179	0.1130

In theory, a production car with an advanced collision warning system may operate by continuously measuring these nine covariates as the vehicle moves along. Meantime, an in-vehicle microprocessor could evaluate the measurements to determine whether a road departure is imminent and a driver warning is warranted. The insights provided in analyses like those seen in Figs. 7 and 8 help determine the conditions under which a warning signal is appropriate.

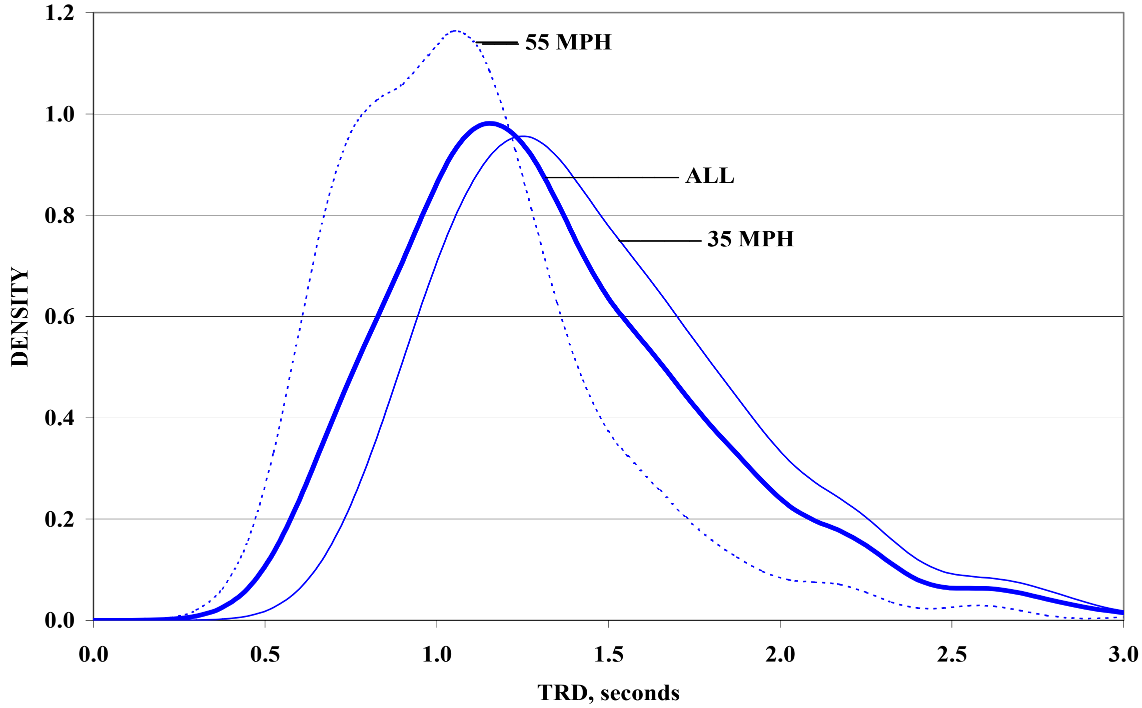

Figure 7. Estimated distributions of time-to-road-departure (TRD) when steering is initiated versus vehicle speed. Drivers tend to steer away later (closer to the time *of* departure) when speeds are higher.

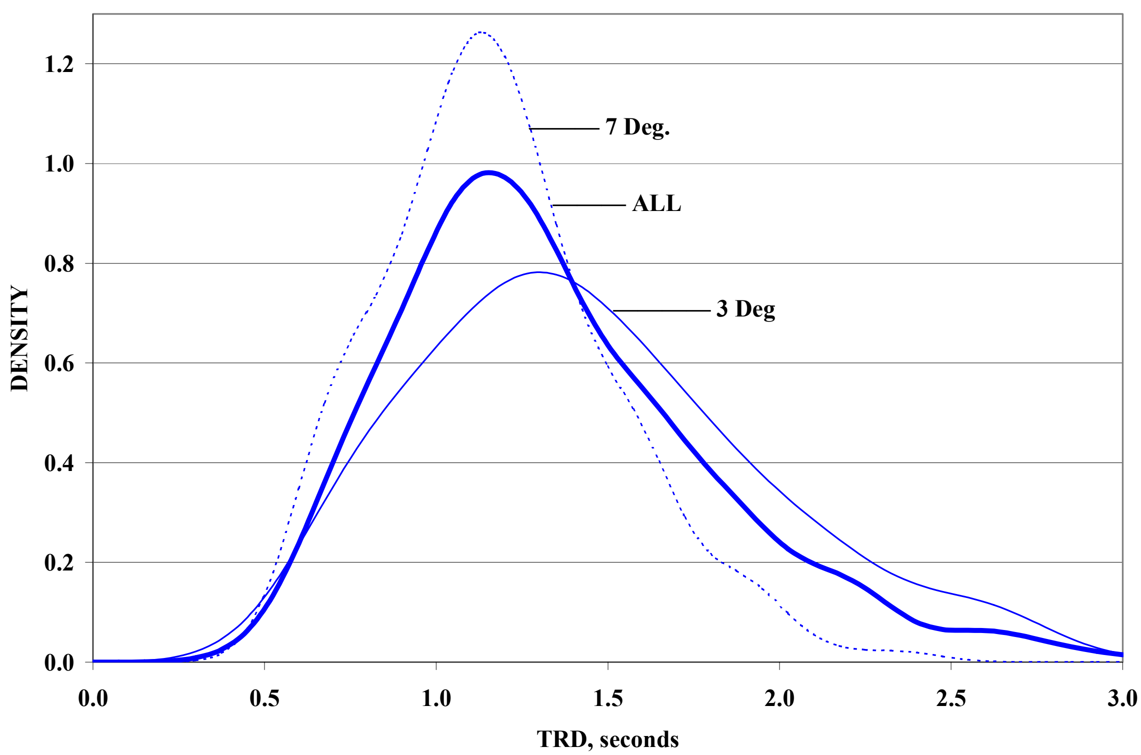

Figure 8. Estimated distributions of time-to-road-departure (TRD) when steering is initiated versus approach angle. Drivers tend to steer away later when approach angles are greater. Also, distributions are tighter when approach angles are greater.

SUMMARY

The performance of a driver in a single-vehicle road departure avoidance maneuver may be characterized by a mathematical expression with nine constants. Five of the constants describe the pre-maneuver vehicle state (speed, heading angle, edge distance, road curvature, and curve entry distance) and four describe the driver response (brake application time, deceleration level, steering input time, and steering angle). A procedure to find the best set of constants is demonstrated, and it shows how the mathematical expression provides close agreement between an actual vehicle path and the path derived from the expression. Thus, it is possible to characterize a road departure avoidance maneuver by a single, nine-covariate data record. This single record may be used in lieu of the several time-histories – made up of thousands of records (one for each time point) – that normally accompany an experimental test record. Such a reduction has many advantages from a data analysis standpoint, and ultimately benefits the development of an in-vehicle crash warning system.

The characterization procedure is demonstrated in an analysis of 1000-plus real driver experiences on a test track. The analysis shows that drivers tend to steer clear from an imminent road departure at time that is closer to the imminent time of departure when travelling at higher speeds and at a more direct angle of approach to the edge of the road.

REFERENCES

Pomerleau D, Everson J (1999), Run-off-road collision avoidance using IVHS countermeasures, Final Report, DOT HS 809 170, Department of Transportation, Washington DC.

Burgett AL, Gunderson, K (2001), Crash Prevention Boundary for Road Departure Crashes – Derivation, NHTSA Technical Note, Office of Vehicle Safety Research, Department of Transportation, Washington DC, 2001, September 2001.

Barickman F, Burgett A, Rau P, Smith D, Srinivasan, G (2002), Preliminary Analysis and Models of Driver Responses to an Impending Lateral Crash, National Highway Traffic Safety, Administration, Office of Advanced Research and Analysis, Advanced Technology Division, NPO-113, Washington, D.C. 20590, December 2002.

Martin PG, Burgett AL (2001), Rear-end Collision Events: Characterization of Impending Crashes, Proceedings of the 1st Human-Centered Transportation Simulation Conference, The University of Iowa, Iowa City, Iowa, Nov 4-7, 2001.

SAS Institute Inc. (1999), Chapter 33 - The KDE Procedure, SAS/STAT User's Guide, Version 8, Cary, NC: SAS Institute Inc., 1999.