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Terry D. Day
Engineering Dynamics Corp.

L. Daniel Metz
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ABSTRACT

Traditional vehicle simulations use two methods of modeling driver inputs, such as steering and braking. These methods are broadly categorized as "Open Loop" and "Closed Loop". Open loop methods are most common and use tables of driver inputs vs time. Closed loop methods employ a mathematical model of the driving task and some method of defining an attempted path for the vehicle to follow. Closed loop methods have a significant advantage over open loop methods in that they do not require a trial-and-error approach normally required by open loop methods to achieve the desired vehicle path. As a result, closed loop methods may result in significant time savings and associated user productivity. Historically, however, closed loop methods have had two drawbacks: First, they require user inputs that are non-intuitive and difficult to determine. Second, closed loop methods often have stability problems. This paper describes a newly developed driver model that appears to hold significant promise in addressing both of these areas. The paper describes the basic vehicle driver model and path generator. Next, the paper provides an intuitive basis for reasonable user inputs. Finally, the paper provides some interesting examples of the use of the vehicle driver model for real-world applications.

MOTOR VEHICLE HANDLING simulation usually has as a goal the duplication of measured experimental data. Handling simulation is also used to assist in the reconstruction of real-world motor vehicle crashes using evidence (e.g., tire marks) gathered at the crash site. Quite often, the chief criterion is to duplicate the actual path followed by the vehicle during an event. To perform the simulation (once the required vehicle parameters have been assigned), the user assigns an initial position and velocity for the run. Next, a set of assumed driver controls (steering, braking, throttle and gear selection) is supplied. The run is then executed and the resulting simulated path is compared to the actual (measured) path. If an acceptable match is achieved, the user concludes the assumed driver controls are reasonable estimates of those used during the experiment. If the match is not acceptable, the user modifies the initial conditions or driver controls as required to improve the match.

The procedure described above is referred to as open-loop simulation because the user is responsible for selecting the driver controls required to cause the vehicle to follow the desired path. These driver controls are normally supplied in tables of driver inputs vs time. As shown in Figure 1, the user is responsible for assessing the error between the simulated and actual path, determining the cause of the error, and estimating the necessary corrections to the driver tables for each simulation run. This trial-and-error procedure continues until an acceptable match is achieved between the simulated and measured path. This procedure often becomes very time consuming, and convergence to the actual path is not guaranteed because of the inherent nonlinearities involved, and concomitant lack of superposition.

An alternative method, called closed-loop simulation, has also been used. Closed-loop simulation employs a mathematical model of the driving task and some method of defining an attempted path for the vehicle to follow. The driver model is responsible for assessing the error between the simulated and measured path and making the necessary

* Numbers in brackets designate references found at the end of the paper.

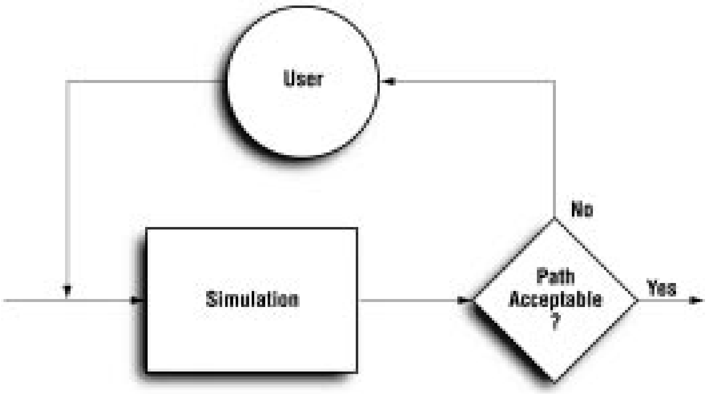

Figure 1 - User-in-the-loop control system for driver inputs (open loop).

corrections to the driver inputs. Rather than waiting until the end of the run, the driver model is executed at each timestep during the run. The driver model receives real-time feedback during the run based on the current path error and acts as the controller in a closed-loop driver/vehicle model. Thus, the driver controls are updated during the run and the vehicle inherently attempts to follow the prescribed path. The trial-and-error associated with open-loop simulation is eliminated, and a great time savings often occurs.

A new driver model has been developed for use in the HVE simulation environment [1]. The purpose of this paper is to describe this model, called the HVE Driver Model, compare it to its predecessors and provide some examples of its use.

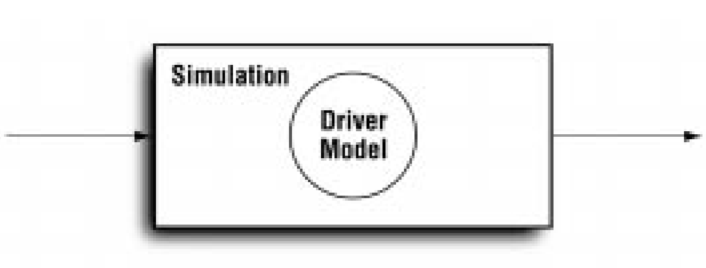

Figure 2 - Driver-in-the-loop control system for driver inputs (closed loop).

LITERATURE REVIEW

The HVE Driver Model is a direct application of a mathematical model of a human control system. The scientific literature on human control theory and performance is rich and large. A complete discussion of control theory is beyond the scope of this paper. For a thorough background, the reader is referred to the references found at the end of this paper. What follows is a review of human control performance.

Closed-loop manual control systems have been classified according to the nature of the input to the human operator [2].

A *compensatory* control system is one in which the operator has a single input, **r(t)**, the error signal, *e*, or difference between system response and desired system response, **y(t)**; see Figure 3a. y_H and y_C are human controller transfer function and the plant transfer function, respectively. The human task is to null the instantaneous error through the use of the controller input vector, **u**. Most human operator models assume a compensatory system. The HVE Driver Model is a compensatory control system; **r(t)** is the steering input, **y(t)** is the vehicle response, **e** is the path error and **u** is the vector of driver correction descriptors.

A *pursuit* control system is one in which the instantaneous reference input **r(t)** and process output **y(t)** are displayed to the operator separately and independently. The operator can therefore distinguish the individual properties of these two signals by direct observation; see Figure 3b.

A *preview* control system is similar to a pursuit system except that the human operator has available a true display of **r(t)** from the present time until some time, *t*, into the future; see Figure 3c.

Finally, a *precognitive* or *anticipatory* control system is one in which the operator has foreknowledge of the input other than from a direct and true view of it; see Figure 3d.

The simplest kind of manual-control task to analyze and model is continuous, one-dimensional tracking in the compensatory control mode. The operator's task is to make the output **y(t)** of the controlled process (or vehicle) correspond as closely as possible to a reference input **r(t)**. There are several classes of variables involved in even such an idealized task, including:

- *Task Variables*: reference input signal(s) **r(t)**, disturbance inputs, the dynamics of the vehicle being controlled, what and how information is displayed to the operator and the control device or manipulator by which the operator acts on the controlled vehicle.
- E*nvironmental Variables*: additional task requirements, vibration, ambient illumination and temperature.
- *Operator-Centered Variables*: training, motivation, skill and fatigue.
- *Procedural Variables*: instructions for the given task, order of presentation of trials, features of the experimental design or measurement features and the control criteria specifying the values of different trade-offs among objectives (the "payoff") and resources used (effort, time, errors).

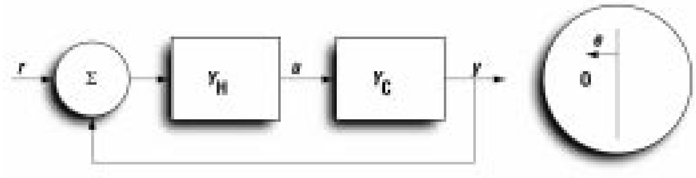

Figure 3a - Compensatory control system.

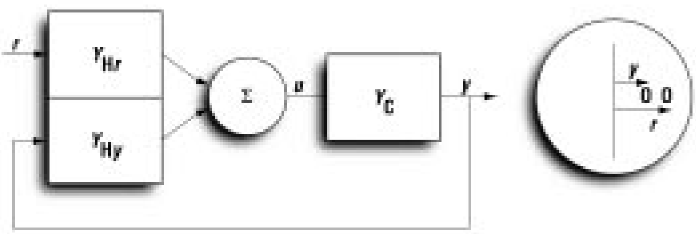

Figure 3b - Pursuit control system.

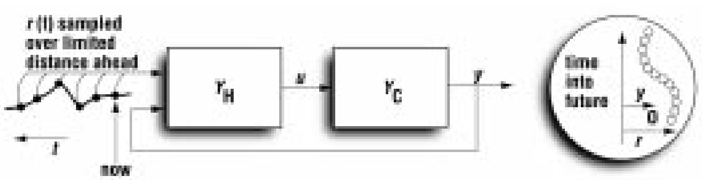

Figure 3c - Preview control system.

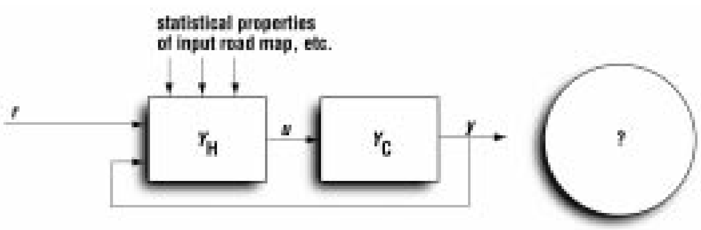

Figure 3d - Precognitive control system.

The simplest form of the human operator models proposed has been that of a constant coefficient linear differential equation relating control output to perceived error [3,4,5]. Two important modifications were quickly added to this basic model. First, an assumption of an unavoidable component of random noise or *remnant* was added to the operator's linearly determined output, which cannot be described by a best-fit, constant coefficient linear differential equation. Second, all parameters for the human operator were assumed *constant* so long as the task variables of the tracking situation remained unchanged.

In synthesizing a first-approximation linear differential equation model of the human operator, three properties are immediately suggested by intuition:

- *Reaction Time Delay*: Simple reaction time experiments reveal an absolute minimum-time reaction time delay or refractory period $t_r > 0.15$sec [3,4,5], which includes neural synaptic delays, nerve conduction time and central processing time as well as the time needed to make a just-measurable response. This time delay is continuous throughout the control task, unlike an initial perception/reaction time, which occurs only once at the beginning of the control task (unless the task stimulus changes during the event).
- *Gain*: Any feedback control loop will require a gain as large as possible, consistent with stability, to have reasonably good response.
- *Neuromuscular Lag*: Once a muscle is commanded to move, the muscle inherent viscosity and inertia, combined with the asynchrony of muscle fiber contraction would be expected to result in an exponential-like response, typically for humans with a time constant on the order of $0.1 < t_n < 0.2sec.$ [3,4,5]

Combining the above properties produces a model of the form:

$$Y_{human} = \frac{Ke^{-\tau_r j\omega}}{1+\tau_n j\omega} \qquad \textit{eq. 1}$$

Such a "crossover" model is precisely what was proposed in [4].

Control takes place in the time domain and not the jω (frequency) domain. So, it is natural to consider time-domain modeling of the human as a controller. Furthermore, human operators usually have more than one task to control. For example, in a simple freeway driving control task, the driver is required to regulate lane position, speed and distances from other vehicles simultaneously.

Modern control theory and multi-variable analyses are synonyms. Human controller models have been proposed [5,6] with the elements described above (t_r, t_n and K) in the standard state-space model form:

$$\dot{x} = Ax + Bu \qquad \text{eq. 2}$$
$$y = Cx + Du$$

where **A, B, C** and **D** are matrices of coupling coefficients, **x** is the vector of state variables, **u** is the vector of control inputs and **y** is the output vector.

As soon as multiple tasks are to be controlled simultaneously, the potential for task interference is present. Studies show that under such conditions, human control performance is *sampled-data* rather than continuous [8,9]. Under such circumstances, difference, rather than differential, equations are used to describe the human controller.

Because humans can never be as consistent as machines, *time variability* of human performance is important. This is not only true of intentional control generation but also of remnant. Both approaches have been previously considered in the literature [10,11]. The same remnant approach taken in [3,4,5] was used in these works, albeit in the time, instead of frequency, domain.

It is only natural for time domain linear models to be approached from the viewpoint of *optimal control* [12,13]. Human control performance, especially in compensatory and pursuit control tasks, essentially consists of time regulation of integrated error, *i.e.*, minimization of an *Index of Performance* (IP) of the form:

$$IP = \int_0^{\tau} \left(x^T Q x + u^T R u \right) dt \qquad \text{eq 3}$$

where **x** and **u** are state and control variable vectors, respectively, and Q,R are price or penalty matrices. Obviously, the matching between predicted and actual human performance depends on the choice of elements in the Q,R matrices. This approach is natural because it psychologically and physiologically mimics what we observe in the human control environment.

Finally, we realize that human control is highly *adaptive.* A driver can readily go from one vehicle to another one with very different vehicle dynamics characteristics without a long (or any) period of training. Adaptive control, particularly *Model Reference Adaptive Control* (MRAC) has been highly studied in many theaters in addition to the area of human control [14,15,16]. In such situations, the interest is in control of plants, which have changing dynamics due to drift, wear, *etc.* This area has little interest to the driving task of an individual vehicle except for sudden changes in vehicle performance, *e.g.,* a tire blow-out. Even then, the *rate* at which the human controller can adapt may be an important factor in the study, not just the level of adaptation required.

PRIOR SIMULATIONS

The use of a driver model in vehicle simulation is not new. A review of early simulations reveals that the original HVOSM included a driver model [19]. The model included path following, speed maintenance, speed change and skid recovery modes of operation. The input parameters required by the model are described in reference 19. The inputs were very non-intuitive (e.g., "Driver's Estimate of Acceleration Gain"). No examples of the model's use were found in the literature.

The HVOSM model was updated in 1984 [20]. The new driver model was greatly simplified, when compared to the original model. The new model applied a steer correction factor according to the path error calculated at a user-defined distance, L_{probe}, ahead of the vehicle. L_{probe} was assigned by the user. The recommended value was *0.25xVelocity*, i.e., if the initial velocity was 35 mph (51.3 ft/sec), the user would assign a distance of 0.25x51.3 = 12.83 ft for L_{probe}. The steer correction factor, P_{gain}, also user-assigned, represented the required steer correction. $1/L_{probe}$ was the recommended value, i.e., if L_{probe} was 12.83 ft, the user would assign P_{gain} equal to 1/12.83, or 0.078 rad/ft. A steer correction damping factor, Q_{gain}, was also assigned by the user. $1/10L_{probe}$ was the recommended value. Thus, in our example, Q_{gain} would be 1/(10x12.83), or 0.0078 rad-sec/ft. The basis for the recommended values of L_{probe}, P_{gain} and Q_{gain} has not been found in the literature (see **Discussion**). In reference 20, the model was used to study the effect of highway cross slope on lane change maneuvers. A passenger car and a truck were simulated in the study. In general, the results were satisfactory, although stability problems were encountered for the truck simulations. The problem was eliminated by changing the value of P_{gain} to $1/2L_{probe}$ and Q_{gain} to $1/5L_{probe}$.

The updated HVOSM model also included a variable torque mode. This mode calculates the steering torque inputs, rather than the steer angle inputs, required to follow the desired path. However, this mode of operation was never fully implemented.

The Phase 4 model included a driver model (the authors called it a *path follower*) [21,22]. The model was more simplified than either HVOSM model. Program inputs included a user-assigned table of X,Y path coordinates (linear interpolation was used between coordinates), a driver time lag and a preview interval. The model calculated an estimated path over the preview interval, then divided this interval into 10 segments and minimizes the squared error between the estimated path and calculated path for each of these segments. An example of the use of the Phase 4 path follower is included in [21]. Essentially, this model represents a crude form of optimal control.

The U.S. National Aeronautics and Space Administration (NASA) has conducted significant research into the subject of control systems and limitations of the human operator as an element within such systems. The Bioastronautics Data Book [23] includes a complete chapter on human control capabilities. Much of the work presented in the Bioastronautics Data Book was based on work performed at Systems Technology during the sixties by McRuer and Weir [3,4,5]. A neuro-muscular filter represents a simplified model of the physiological human operator which incorporates delay time, lead time and lag time corresponding to the neurological and muscular systems of a human driver. A neuro-muscular filter was used in the HVOSM models [19,20]. The filter model was, in fact, based on the work of McRuer and Weir.

DESCRIPTION OF HVE DRIVER MODEL

The approach used by the HVE Driver model is based on the modified HVOSM model. However, the modified HVOSM model required a user-supplied preview distance (L_{probe}) as input. Research using this approach revealed two shortcomings: First, the user had to calculate all model input parameters according to the initial vehicle speed. Second, the model had no way of altering the input parameters as the vehicle's speed increased or decreased. Thus, the results may become unstable as the vehicle speed changed. Of course, a real human driver compensates for a speed increase by looking further down the road (i.e., increasing the preview distance) as the vehicle speed increases. A third problem was encountered when attempting to use the model for different sized vehicles [20].

These problems were addressed by the practical observation that, because the simulation operates in the time domain, so should the driver model. The basis for this observation is also consistent with general principles of control theory, discussed earlier in this paper. Thus, instead of preview distance, preview *time* was selected for use in the HVE Driver Model. Internally, the HVE Driver Model calculates the preview distance at each integration timestep, thus helping to ensure stability with varying speed. The details of the algorithm are described below.

Algorithm Description

The HVE Vehicle Driver Model is composed of four components:

- Path Generator
- General Parameters
- Driver Descriptors
- Neuro-muscular Filter

The model inputs are listed in Table 1 and described below. Also refer to **Selecting Model Inputs** later in this paper.

Table 1. Inputs for HVE Driver Model [1].

Parameter*	Description
Path Generator X,Y,Z (in) ϕ,θ,ψ (rad)	User-entered path position and orientation for up to eight locations
General Parameters Start Time (sec) Sample Interval (sec) Driver Preview Time (sec) Max Path Error (in) Max Lateral Accel (in/sec^2)	Parameters used for controlling the driver model
Driver Descriptors Initial Steer Angle (rad) Max Steer Velocity (rad/sec) Steer Correction Gain (rad/sec) Steer Correction Damping (rad)	Parameters defining driver steering characteristics
Neuro-muscular Filter Driver Lag Time (sec) Driver Lead Time (sec) Driver Time Delay (sec)	Parameters defining the human driver physiological characteristics

**Program units are shown in parentheses. Any desired units may be selected by the user.*

Figure 4 - Spline path definition for up to eight user-defined vehicle positions and orientations.

Path Generator

The path generator uses a minimum of two and a maximum of eight 3-D positions and orientations to define the attempted path. The path is constructed from a 3-D spline curve passing through each user-specified location and tangent to the roll, pitch and yaw angles for each location (see Figure 4). As a spline curve, it is constructed of piece-wise linear segments 12 inches, or less, in length. The HVE Driver Model turns off when the preview distance reaches the last user-entered path position.

General Parameters

The general parameters provide control over the path follower algorithm. The driver model need not start at the beginning of the simulation. Termination occurs if the current level of vehicle lateral acceleration or steering wheel angular velocity exceed the user-defined maximum tolerance levels.

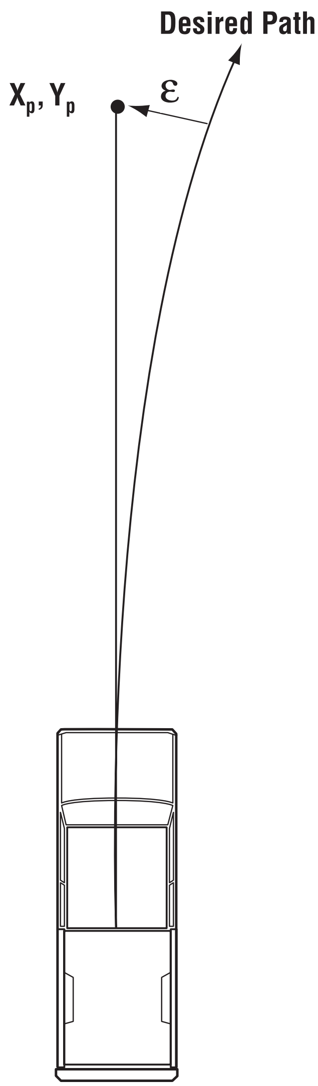

Figure 5 - Driver preview point, X_p,Y_p, and path error, ε.

Driver Descriptors

The driver descriptors describe the operator characteristics that determine how the driver attempts to control the vehicle. The primary controlling factors are the *Steer Correction Gain* and *Steer Correction Damping*. The simulation need not begin at zero steer angle.

Neuro-muscular Filter

The driver neuro-muscular filter represents a mathematical model of the human operator performance in a man-machine control system. The members of this group are described later in this paper.

Calculation Procedure

While executing, the simulation model calculates the vehicle's current position and velocity according to the current forces and moments acting on the vehicle. For the current vehicle position and velocity, the HVE Driver Model calculates the driver preview distance, $S_{preview}$, for the current sample interval, n:

$$S_{preview} = \tau_{preview} \times u \qquad \textit{eq. 4}$$

where $\tau_{preview}$ is the driver's preview time (i.e., *how many seconds ahead of the current roadway longitudinal position is the driver looking*?) and u is the vehicle's forward velocity component. The earth-fixed coordinates of the point $(X_p,Y_p)_n$ where the driver is looking are then calculated for the n^{th} driver sample. Usually the point X_p,Y_p will not lie on the specified path (see Figure 5). The path lateral error distance, ε_n, from the desired path to $(X_p,Y_p)_n$ is then calculated (note that ε is normal to the desired path at point X_p,Y_p).

If ε_n is greater than the maximum allowable path error, $\varepsilon_{threshold}$, path correction is required. First, the path error rate, $\dot{\varepsilon}$, is calculated for the n^{th} interval using a standard first-order backward difference equation:

$$\dot{\varepsilon} = \frac{\varepsilon_n - \varepsilon_{n-1}}{\Delta t_{sample}} \qquad \textit{eq. 5}$$

where ε_{n-1} is the path error for the previous sample interval and Δt_{sample} is the sample interval. The incremental steer correction for the n^{th} interval is then computed:

$$d\delta_n = \delta_c \varepsilon_n + \dot{\delta}_c \dot{\varepsilon}_n \qquad \textit{eq. 6}$$

where δ_c and $\dot{\delta}_c$ are the user-entered steer correction gain and steer correction damping, described earlier.

The rate of steer correction at the n^{th} interval is:

$$d\dot{\delta}_n = \frac{d\delta_n - d\delta_{n-1}}{\Delta t_{sample}} \qquad \textit{eq. 7}$$

where $d\delta_{n-1}$ is the steer correction for the previous sample interval. $d\dot{\delta}_n$ is not allowed to exceed the user-defined maximum steering wheel velocity, $\dot{\delta}_{\max}$.

Finally, the required steering wheel angle over the n^{th} interval is calculated:

$$\delta_n = d\delta_n + \delta_{n-1} \qquad \textit{eq. 8}$$

where δ_{n-1} is the steer angle for the previous sample interval.

In practice, the allowable steer angle at the axle is limited by the steering stops. Thus, if the resulting steer angle is greater that the steering stop angle, δ is set equal to the steering stop angle.

Selecting Input Parameters

Although the required input parameters (see Table 1) have default values, shown in parentheses below, some experience is helpful in understanding the effect of each parameter on the resulting vehicle path. The following provides some guidelines on the selection of input parameters used by the HVE Driver Model.

Time Start (0.0 sec) - Modifying this value delays the start of the driver model. Prior to reaching *Time Start*, the steer angle is normally zero, although the programmer of the simulation model may also choose to use the open loop steering table.

The *Time Start* may also account for a perception/decision/reaction time as well (i.e., the time required to perceive and decide to react to the stimulus in a complex environment). In this case, *Time Start* should be set according to the desired perception/reaction time. For example, if the stimulus (e.g., a flat tire) begins at t = 1.3 seconds into the simulation and the driver perception/reaction time is estimated to be 0.5 seconds for a steering input response (a braking response time would obviously be longer), *Time Start* should be set to 1.80 seconds (1.3 + 0.5).

Sample Interval (0.10 sec) - Modifying this value increases or decreases the interval at which the driver model queries the desired path. The results are not overly sensitive to this value, however, if increased too much (say, beyond a factor of 2), the driver model will acquire dynamics that resemble a lightly damped oscillator (i.e., it will overshoot the desired path, then over-correct to regain control). Entering a smaller value may be useful for modeling a race car driver, but has a diminishing return for most drivers, and increases execution time.

Driver Preview Time (1.0 sec) - This value determines the distance ahead of the vehicle the vehicle is aiming at. For example, if the preview time is increased to 1.5 sec and the vehicle is traveling 88 ft/sec, the driver aims the vehicle at a point 132 ft ahead. Longer preview times produce more damping and a sluggish response, especially for complex paths.

The estimate for *Driver Preview Time* is somewhat arbitrary. An upper limit might be established by the two second rule (that is, a driver should follow another vehicle no closer than the distance traveled in 2 seconds). A lower limit of, say 0.5 seconds, can be established simply by driving while looking ahead of your vehicle by no more than the distance traveled in 0.5 seconds; most people find this quite uncomfortable.

Maximum Path Error (0.08 ft or 1 inch) -Increasing this value significantly causes the vehicle to overshoot the desired path; decreasing the value causes increased steering activity and a closer match with the desired path. The HVE Driver Model has included a null band within this range. This addition greatly reduces noise and oscillation in the vicinity of zero path error, compared with the earlier models (e.g., [20]). The addition also makes it unnecessary to change this value from its default.

Driver Comfort Level (0.4g) - Increasing this value prevents termination during high-G maneuvers. Increasing it too much will allow the vehicle to spin out. Although a spinout does not invalidate any assumptions made by the HVE Driver Model, the default values for *Steer Correction Rate* and *Steer Damping* Rate (see below) may not be sufficient to result in regaining vehicular control (of course, this is also true for a real vehicle/driver system).

Initial Steer Angle (0.0 deg) -This value may be changed if the simulation begins in a turn with an initial vehicle steer angle. Although the HVE Driver Model will calculate the required steer angle during the first timestep, the assumption of zero steer angle for a condition of significant path curvature will result in the calculation of a significant (and possibly unrealistic) initial steer velocity. Thus, if an initial steer angle exists, it should be entered.

Max Steer Velocity (720.0 deg/sec) - Increasing this value prevents termination during an extremely dynamic event, that is, where high steering wheel velocities are required to follow the desired path. It should be noted that, except for very short duration maneuvers, most drivers are not capable of higher steer velocity inputs.

Steer Correction Rate (240 deg/sec) and Steer Damping Rate (12 deg/sec/sec) - Both steer correction rate and steer damping rate are associated with human physiological control limitations. These parameters represent the controller input vector, **u** (see Figure 3a).

For small-amplitude inputs, steering rates as high as 2400 deg/sec may be attained for brief periods. However, for continuous and/or larger amplitude steering (e.g., steering times of ~ 0.25-0.5 seconds, steering amplitudes ~ 180 degrees or so at the steering wheel), steering rates fall off rapidly. For larger amplitudes and longer durations of steering, maximum steering rates of ~ 300-360 deg/sec are more reasonable.

The above rate limitations imply step or ramped steering inputs. There are also *frequency limits* to human steer performance. Harmonic or zigzag steering of any duration or amplitude (e.g., a rapid double-lane-change maneuver) cannot be sustained by most drivers at frequencies greater than about 1 Hz. Shorter duration, part cycle reversing steering inputs that are quasi-harmonic may have frequency content or non-negligible power as high as 3 Hz or so for typical drivers.

Little reliable data exist for realistic damping rates during rapid steering. However, it is clear that the damping ratio of most drivers in such a control task is small, on the order of $\zeta > 0.1$, and strongly dependent on the task involved (compensatory, pursuit, etc.). Considerable overshoot is always present in measured driver steer data, and, as overshoot is usually considered detrimental to the driving task, it is an error on the side of safety to employ a low value for this coefficient. Parametric testing by the authors has revealed that the *Steer Damping Rate* should be approximately 5 to 10 percent of the *Steer Correction Rate.*

It is also important to recognize that individual vehicle power steering systems may impose limits low enough that the steering rates achievable by drivers are greater than those supportable by the system fluid dynamics. In that case, the limitations on steering rate and damping may be vehicle-imposed and not driver imposed, and should be adjusted for the particular vehicle involved.

The preceding paragraph suggests these rates are also a function of the vehicle's steering gear ratio. Parametric studies with the HVE Driver Model confirm this. Lower ratios (higher numerical ratios), such as those used on highway trucks should be increased according to the vehicle's steering gear ratio. Because a typical truck has a steering gear numerical ratio approximately 50 percent higher than a typical passenger vehicle, an increase in *Steer Correction Rate* and *Steer Damping Rate* of 50 percent above the default values is a good estimate.

Driver Lag, Lead and Delay Times (0.05, 0.0091 and 0.15 seconds, respectively) - Modeling of driver lag implies that, even if a step command in steering wheel angle is desired by the driver, (s)he cannot create instantaneous steer torques. Considerable evidence indicates that, in the driving task involving lane monitoring, driver lag can be modeled as a first order system with a time constant in the range of 0.1-0.2 seconds [2,3,4]. A driver could therefore be expected to reach full control response in approximately 4 time constants, or 0.4-0.8 seconds.

These inputs are used by the driver filter and exist continuously throughout the maneuver. These inputs are fundamentally different from perception/reaction time (see *Time Start*, above, and **Discussion**, later in this paper).

Drivers also exhibit precognitive lead and/or anticipatory control characteristics associated with task learning and history, familiarity with roadway and traffic conditions, etc. At present, there is no realistic way to model this characteristic of driver behavior.

Table 2. Outputs for HVE Driver Model [1].

Parameter*	Description
Termination Conditions Excessive Lateral Accel Excessive Steering Velocity	Results leading to termination
Time-dependent Outputs Steering Wheel Angle (rad) Steering Wheel Ang. Vel (rad/sec) CG Path Error (in) Preview Distance (in) Path X-Coord (in) Path Y-Coord (in) Path Error at Preview Distance (in) Preview X-Coord (in) Preview Y-Coord (in)	Parameters defining current vehicle conditions, available in output tracks (Key Results or Variable Output)

**Program units are shown in parentheses. Any desired units may be selected by the user.*

Driver Model Outputs

The results from the HVE Driver Model are output at each user-defined output interval. The individual parameters are shown in Table 2.

Termination Conditions

The HVE Vehicle Driver Model terminates under the following two conditions:

- *Maximum Lateral Accel* - The current level of lateral acceleration is compared to the user-entered value for maximum lateral acceleration (see Table 1). If the current level is higher than the user-entered maximum, the run terminates with a diagnostic. This condition simulates the point where a driver has reached his/her maximum level of discomfort and is not able (or willing) to continue attempting to maintain vehicular control.
- *Maximum Steer Velocity* - The current level steering wheel angular velocity is computed with the user-entered Maximum Steer Velocity (see Table 1). If the current level is higher that the user-entered maximum, the run terminates with a diagnostic. This condition simulates a limit in the driver's ability to steer the steering wheel and/or power steering system limitations.

Time-dependent Results

Because the HVE Driver model operates in the time domain, the simulation output results are, of course, time-dependent. The results are found in the HVE Vehicle Driver Group *output tracks*. The results include current steering wheel angle and angular velocity, vehicle path error, current preview distance, CG path X,Y coordinates, path error at preview distance and X,Y coordinates at preview distance (ε and X_p, Y_p, respectively; see Figure 5).

SAMPLE APPLICATIONS

The following applications illustrate the use of the HVE Vehicle Driver Model:

- S-Turn (Lane Change) Maneuver
- Blow-out
- Winding Road

The SIMON [24], EDVSM [25] and EDVDS [26] Vehicle simulation models were used in all examples. HVE Driver Model default values were used, except for the Winding Road simulation. In that simulation, the *Steer Correction Gain* and *Steer Correction Damping* were increased by 50 percent to account for the heavy truck steering gear ratio, and the *Neuro-muscular Filter* was turned off because our goal was simply to cause the vehicle to follow a path, rather than to comment on driver steering inputs.

S-Turn Maneuver

This example is an extension of the work performed in reference 20, HVOSM Studies of Highway Cross Slope Design. In this study, HVOSM and Phase 4 were used to quantify the response of various vehicles to a simulated lane change maneuver. The selected roadway was a 2-lane highway with 2 and 4 percent cross-slope on each side (break at the centerline without rounding). The desired path was derived from research conducted at the Texas Transportation Institute by Glennon and Weaver [27,28]. In general, the path curvature for a relatively severe lane change maneuver was found to be 1132 feet at highway speeds. The forward acceleration was 0.1 g. The maneuver was preceded by a one second acceleration period; the lane change occurred over a 3 second time span. The resulting 4-segment path is shown in Figure 6. The example uses a Generic Class 3 Passenger Car [29] with a 105.1 inch wheelbase. The environment was a 2-lane highway with 12 ft lane widths and 2 percent cross slope (see Figure 7). The initial speed for the maneuver was 55 mph.

The results of the simulation are shown in Table 3. Conditions are shown for each of the five path nodes. The path error is well within acceptable limits, reaching a maximum of -1.2 ft. at node 3. The maximum steering wheel angle was -6.9 degrees at node 2 (although not displayed in the table, the largest steering angle was 11.1 degrees between nodes 3 and 4). The maximum lateral acceleration reached -0.11 g at node 2.

To test the stability of the HVE Driver Model, the experiment was executed a second time after reducing the initial speed to 35 mph from 55 mph. No other changes were made. The results, shown in Table 4, are quite comparable to the results from the 55 mph test.

Blow-out

This example represents a simple and objective method for determining the driver inputs required to regain control following a tire blow-out. The procedure is as follows:

Step 1 - Assign a straight path using two path positions. Assign an initial velocity of 65 mph. The experiment is set up on a digital proving ground (see Figure 8) to provide the user visual feedback regarding the vehicle response. The width between lane stripes is 20 feet.

Step 2 - Use the HVE Tire Blow-out Model to simulate an air loss occurring 2.0 seconds into the run. Although any tire(s) could be selected for the experiment, the left rear tire was selected because rear tire air loss is potentially de-stabilizing, depending on the driver's response.

Step 3 - Turn on the HVE Driver Model, using the default driver parameters. Set the *Start Time* to 2.5 seconds to simulate a 0.5 second driver perception/reaction time following the blow-out.

Step 4 - Execute the run.

The results (see Table 5) show the resulting path at a nominal 0.5 second intervals. Because the desired path is a straight line,

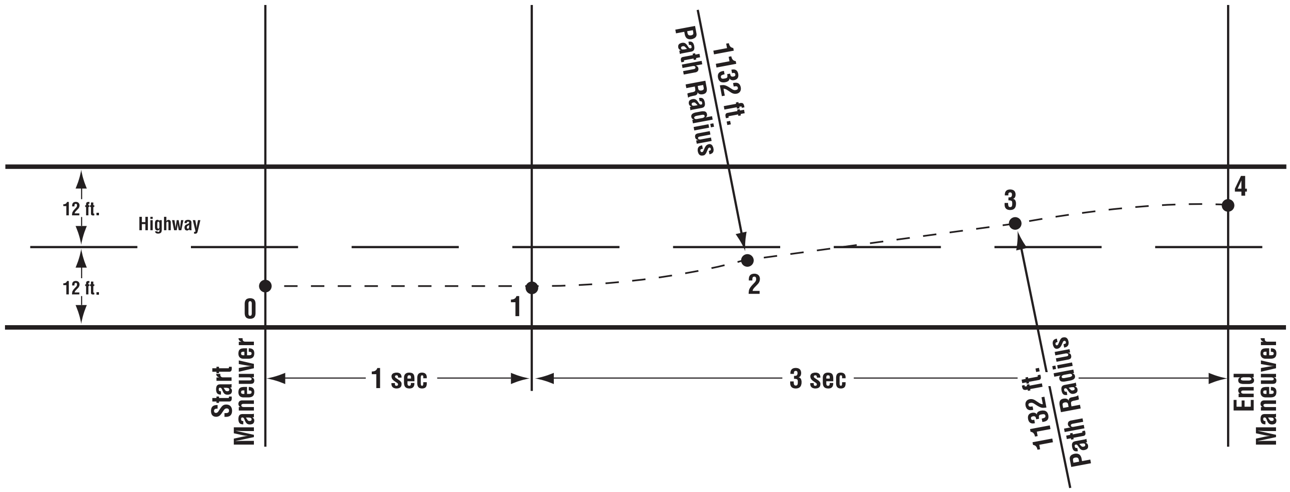

Figure 6 - Schematic of path used for S-turn (lane-change) maneuver simulation.

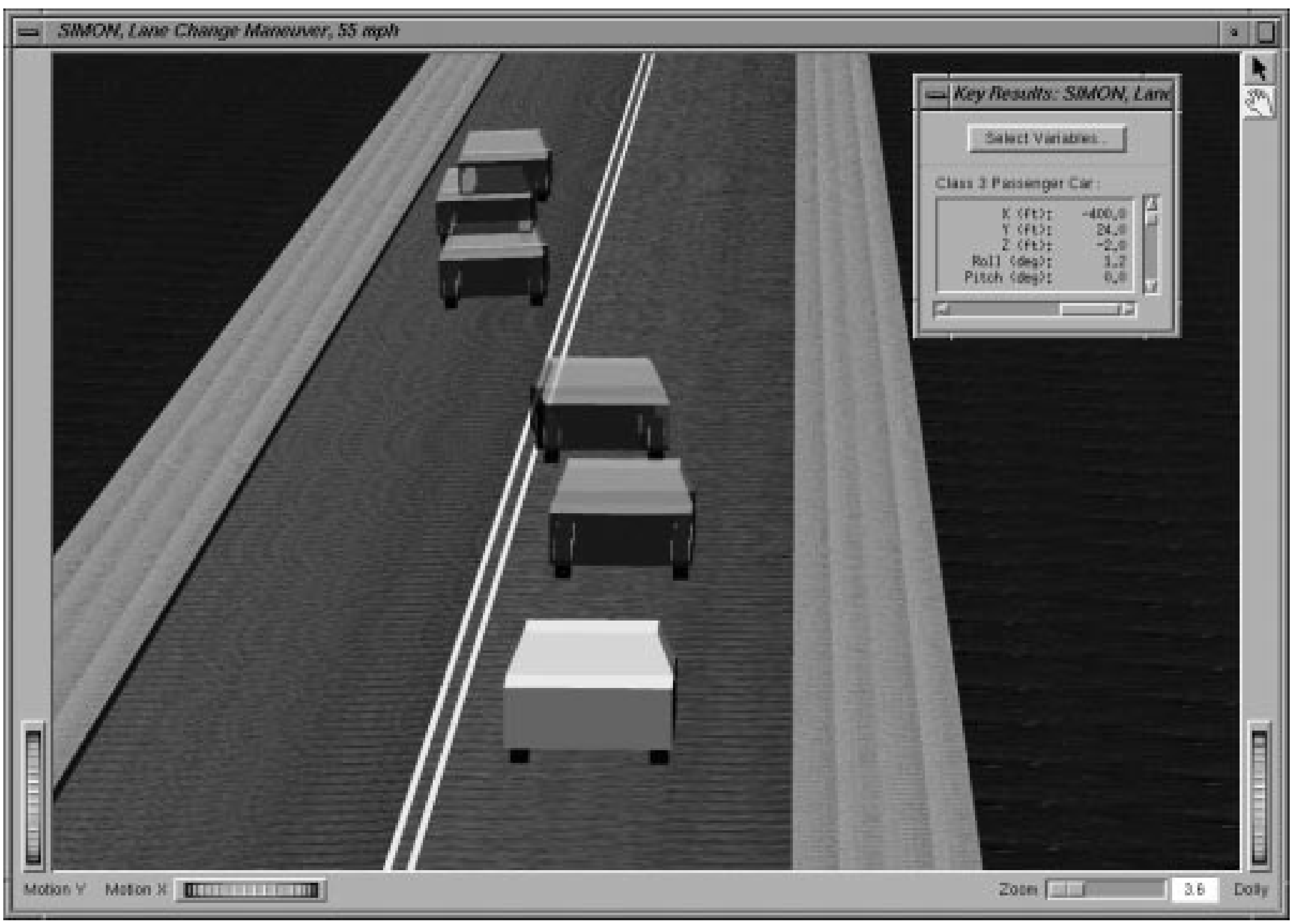

Figure 7 - 2-lane highway environment used for S-turn (lane-change) maneuver simulation.

Table 3. Results of S-turn (lane change) maneuver at 55 mph initial velocity.

Node No	Time (sec)	Velocity (mph)	Distance Traveled (ft)	Path Coordinates (ft)				Error Dist (ft)	Steering Wheel Angle (deg)	Lateral Accel (g)
				As Defined		Simulated				
				X	Y	X	Y			
0	0.00	55.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02
1	1.00	57.1	82.3	82.3	0.0	82.3	0.0	0.0	-5.6	-0.05
2	1.82	59.0	151.2	151.2	2.1	151.2	1.3	-0.7	-6.9	-0.11
3	3.26	62.2	279.5	279.2	9.9	279.2	8.7	-1.2	2.9	0.02
4	4.00	63.9	348.4	348.1	12.0	348.1	12.5	0.5	0.0	0.02

Table 4. Results of S-turn (lane change) maneuver at 35 mph initial velocity.

Node No	Time (sec)	Velocity (mph)	Distance Traveled (ft)	Path Coordinates (ft)				Error Dist (ft)	Steering Wheel Angle (deg)	Lateral Accel (g)
				As Defined		Simulated				
				X	Y	X	Y			
0	0.0	35.0	0.0	24.0	0.0	24.0	0.0	0.0	0.0	0.02
1	1.52	39.0	82.3	82.3	0.0	82.3	-0.1	0.1	-5.1	-0.04
2	2.68	41.1	151.2	151.2	2.1	151.2	1.4	-0.7	-6.9	-0.06
3	4.62	47.7	279.2	279.2	9.9	279.2	9.6	-0.3	2.7	0.03
4	5.59	50.2	348.1	348.1	12.0	348.1	12.8	0.8	0.0	0.02

the path error represents the deviation from a straight line. Notice the maximum deviation is 0.9 ft; the maximum steer angle is -10.7 degrees, (the largest steer angle is actually -11.6 degrees, occurring at 4.60 seconds) and the maximum lateral acceleration is -0.09 g. In general, the results show a rather simple and stable maneuver. The steering wheel angle is graphed in Figure 9.

Winding Road

This example simply illustrates the use of the HVE Driver Model to determine the driver inputs required to follow a long and winding road. For purposes of this example, a 1-1/2 mile section of a narrow 2-lane highway were digitized and a 3-dimensional *digital terrain map* (DTM) was prepared. A tractor towing a loaded 45-ft. semi-trailer was used in the study. A portion of the environment is shown in Figure 10, along with several target positions.

The results are shown in Table 6. The target positions are selected as the reference points. The maximum path error is -9.3 ft at node 3. The largest steer angle is 159.8 degrees, also at node 3. The largest lateral acceleration is 0.29 g at node 2. This is a good example of an attempted maneuver that the vehicle is not able to perform at the given speed and steering correction rate, as suggested by the large path error.

LIMITATIONS

The HVE Driver Model is most useful for estimating driver steering inputs for vehicles operating at or near a steady-state condition (i.e., the vehicle is not spinning out). Sideslip is accommodated by the model, however, excessive sideslip will result in loss of control (just as it does for real vehicles and drivers). Termination due to excessive lateral acceleration normally occurs before the vehicle becomes unstable, however, the user can prevent termination by setting the *Maximum Lateral Acceleration* input to an excessively high value). Thus, the model may or may not useful for predicting separation velocity of a vehicle after collision. The HVE Driver Model would be useful only if the vehicle were being steered by its driver; this is not likely after most

Table 5. Results of tire blowout simulation at 65 mph.

Time (sec)	Velocity (mph)	Distance Traveled (ft)	Path Coordinates (ft)				Error Dist (ft)	Steering Wheel Angle (deg)	Lateral Accel (g)
			As Defined		Simulated				
			X	Y	X	Y			
0.0	65.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.0	62.9	187.1	187.1	0.0	187.1	0.0	0.0	0.0	0.0
2.5	62.1	232.9	232.9	0.0	232.9	-0.1	-0.1	3.3	-0.02
3.0	61.5	278.2	278.2	0.0	278.2	-0.5	-0.5	-0.2	-0.02
3.5	60.9	323.0	323.0	0.0	323.0	-0.8	-0.8	4.0	0.04
4.0	60.3	367.4	367.4	0.0	367.4	-0.6	-0.6	-6.9	0.04
4.5	59.7	411.4	411.4	0.0	411.3	0.1	0.1	-10.7	-0.01
5.0	59.1	454.8	454.8	0.0	454.8	0.9	0.9	-5.7	-0.09

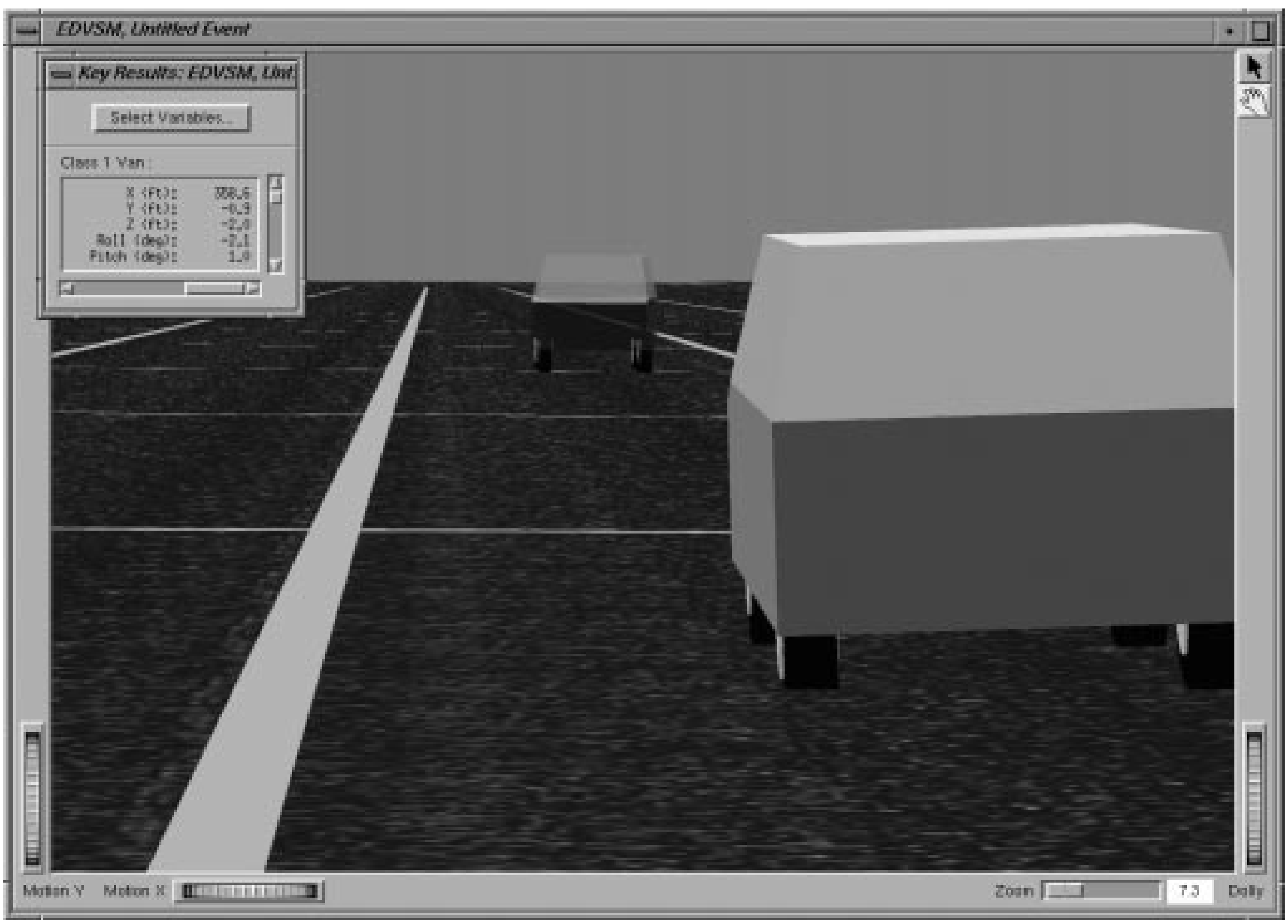

Figure 8 - Digital proving ground environment used for tire blow-out simulation .

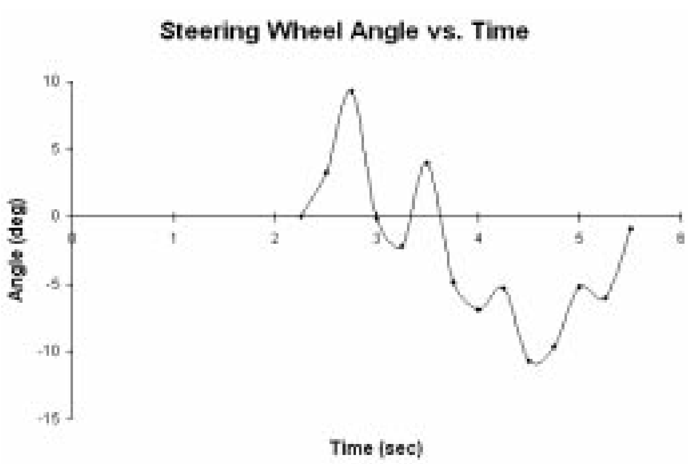

Figure 9 - Simulated steering input for tire blow-out simulation.

collisions. Following collision, the wheels are normally steered by moments at the tire-road shear interface (contact patch), therefore, the *steer degree of freedom model* is a better choice for this type of study.

Although the HVE Driver Model may be used to cause a vehicle to follow a specified path prior to impact, it does not determine *when* the vehicle reaches impact. Thus, using the HVE Driver Model for a multi-vehicle intersection collision, each vehicle will arrive at the intersection at a different time unless the initial positions and velocities are selected properly. An easy way to estimate the correct initial positions and velocities is to allow the vehicles to approach each other using the HVE Driver Model and note the time they reach the desired impact position. Then adjust the initial positions according to the time difference required, given the initial speed, for all vehicles reach the desired positions at the same time.

Figure 10 - Simulation of following a winding road.

Table 6. Results of winding road path simulation.

Node No	Time (sec)	Velocity (mph)	Approx. Distance Traveled (ft)	Path Coordinates (ft)				Error Dist (ft)	Steering Wheel Angle (deg)	Lateral Accel (g)
				As Defined*		Simulated				
				X	Y	X	Y			
0	0.0	30.0	0	141.5	162.5	141.5	162.5	0.0	45.3	—
1	4.70	29.4	205	71.2	-27.9	71.1	-27.9	-0.1	32.9	-0.37
2	9.30	29.2	404	53.6	-222.4	49.1	-223.5	-4.7	124.7	0.29
3	12.35	27.7	524	96.5	-334.8	90.1	-341.9	-9.3	159.8	0.25
4	15.95	28.3	669	205.8	-429.2	202.6	-434.4	-6.1	56.0	0.07
5	21.45	28.0	897	401.3	-542.4	403.1	-540.0	3.0	-118.2	-0.18

**X,Y coordinates for points on the path at the user-defined simulation output interval (0.05 sec) closest to the target positions.*

DISCUSSION

This paper illustrates three examples of the use of a driver model in vehicle dynamics studies. In the first and third examples, the driver model is used simply to find the magnitude of the driver steering inputs required to follow a prescribed path. The precise timing of the steering is of secondary important to these studies - so long as the vehicle successfully negotiates the prescribed path. The second example is substantially different in that the driver model is used to determine both the *magnitude* and *timing* of the driver steering inputs in response to an inherently non-linear dynamic event caused by transient forces at the tire-road interface. In this example, the timing is of primary importance because the transient forces are acting to quickly cause path divergence.

The proper selection of *Steer Correction Rate* and *Steer Damping Rate* is somewhat arbitrary in that there exists a rather large range for these parameters that results in reasonable vehicle behavior. In other words, inputs may be selected that result in a high steering input over a short duration, or a lower steering input over a longer period of time (see Figure 11). This observation is consistent with actual driving experience. Lower steering inputs over a longer time interval would normally be considered smoother driving.

Open-loop simulation, trajectory optimization, inverse vehicle dynamics and use of a *driver model* such as the one described in this paper are four fundamentally different procedures. In open loop simulation, a set of driver commands is supplied to the vehicle model in an attempt to match observed and computed trajectory histories. Of course, the first estimate for driver controls is usually unsuccessful and adjustments are made to the control inputs (and, often, initial conditions) in an attempt to produce a better match between the actual vehicle trajectory and that calculated by the model. Essentially, this is forward vehicle dynamics: controls and initial conditions are supplied to a model and the results are observed and compared to experimental data.

Optimization procedures re-execute the vehicle simulation while applying an algorithm for adjustment of the initial conditions and/or driver inputs. The objective of the adjustment algorithm is to provide a continuously-improving match between the simulated and actual vehicle paths. Previous research has shown that statistical optimization procedures can actually reduce the quality of the simulation because they lack the intuition provided by real-world *physical* feedback [30]. In addition, such optimization procedures can

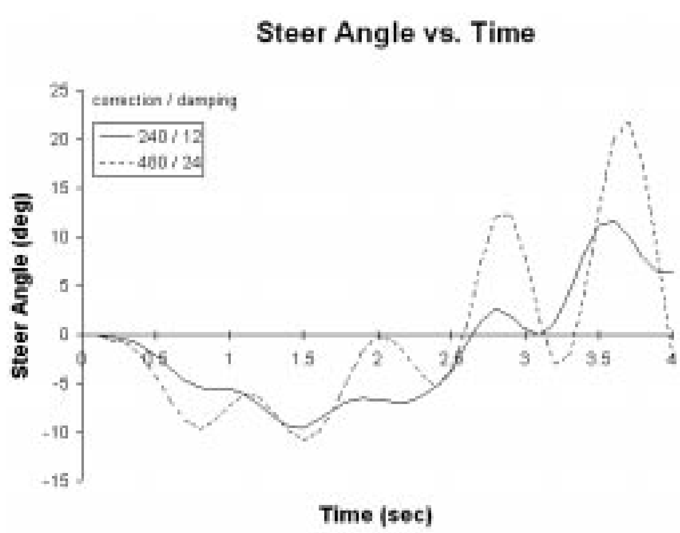

Figure 11 - Comparison of simulated steering inputs for two different steer correction rates, 240 and 480 deg/sec. In each case, the damping is 5 percent of the correction. Both of these inputs result in minimal path error (< 1.5 ft).

only be locally optimal because of the inherently nonlinear nature of limit-performance vehicle maneuvers and simulation. No general global optimization techniques exist for nonlinear systems, particularly those with hard nonlinearities (friction, velocity, etc.). Quasi-global optimization is often performed on systems with smooth or soft nonlinearities through linearization techniques.

Inverse vehicle dynamics begins by taking the actual or desired vehicle trajectory and vehicle model and trying to backward-calculate the controls necessary to achieve that path [34]. While intuitively appealing, the methodology is complex and suffers from all of the drawbacks of other optimization procedures, and can therefore be employed only to the simplest of vehicle models and maneuvers. Even in the case of linear models, issues of controllability and observability are not trivial. Unfortunately, too, simple linear models and maneuvers made by such models are of little interest to the reconstructionist or modeler of real vehicle behavior!

Finally, an in-the-loop driver model is closed-loop in nature, inherently heuristic and intuitively appealing. The driver model responds to real-time feedback that involves a compensatory comparison between the simulated and desired path. In doing so, the model employs a metric highly analogous to the actions of a real driver in a compensatory control task such as lane position monitoring: it continuously changes the steer angle in such a way as to reduce path error.

The term *time delay* in the accident reconstruction field commonly refers to perception/reaction time. However, time delay in a driver neuro-muscular filter is very different from perception/reaction time. In the driver filter, time delay exists continuously throughout the event while perception/reaction time exists only once, at the start of the event. Therefore, perception/reaction time should be entered as a *Start Time* for starting the driver model, not as a delay time. To enter an excessive time delay is essentially modeling an intoxicated driver.

Perception/reaction time may be taken to be 1.5 - 2.5 seconds [32,33]. However, this is the time associated with reaction to an unexpected event, selecting a course of action, and beginning to execute the action or command. The value is almost always associated with braking, not steering. In a lane monitoring control task, the time delay associated with an error detection would be considerably less than 1.5 seconds, perhaps on the order of 0.25-0.75 seconds, depending on driver skill, motivation and roadway condition.

The HVE Driver Model normally terminates after the preview point reaches the last target position. However, the physics program incorporating the HVE Driver Model is free to choose how the model behaves following the last target. Some options are:

- *Zero Steer* - The steer angle becomes zero following the last target
- *Constant Steer* - The steer angle remains constant (equal to the current value) following the last target
- *Default To Steer Table* - The steer control is taken over by the open loop steer table.

The HVE Driver Model is currently implemented as a *path follower* only. No attempt is made to maintain a prescribed following distance or speed.

RECOMMENDATIONS

An important application for the HVE Driver Model appears to be the study of driving while intoxicated. Law enforcement training academies routinely conduct controlled experiments on a closed slalom course wherein officers consume a known amount of alcohol (blood alcohol level is usually measured as well), and are then asked to drive the slalom course. It is recommended that such a study be performed during which vehicle position and velocity are carefully measured. The results could be used to determine input parameters for the driver filter at various blood alcohol levels. Theses results could then be used to help quantify the process of driving while intoxicated and to help highway engineers design safer and more forgiving highways.

The HVE Driver Model determines the driver steering inputs required to follow a user-defined path. The driver model should be extended to determine the throttle or braking inputs required to follow a user-defined velocity profile. Because the HVE Event Editor includes a gear shift table, the model could be extended to determine shift points as well.

The modified HVOSM driver model included an attempt to develop a variable torque path follower. Such a model would determine the steering torque inputs at the tire-road shear interface required to follow a user-defined path. Completion of that initial attempt should be considered.

CONCLUSIONS

1. Closed-loop simulation provides a significant advantage over open-loop simulation. The open-loop, trial-and-error approach used when selecting driver control inputs to mimic vehicle response can be time-consuming. Because vehicle response is nonlinear, no optimization algorithm(s) exists to produce continuously improved results and/or guarantee convergence to the correct result. Furthermore, the optimization process is statistical and has no physical basis in actual vehicle dynamics or driving behavior. By contrast, the driver model proposed in this paper mimics vehicular control by performing in a fashion similar to an actual driver. Because the driver behavior is in-the-loop, convergence to the desired path is inherent. Finally, the driver model is adjustable enough to accommodate known aberrations in driver behavior (e.g., levels of intoxication).

2. For the single lane change and tire blow-out maneuvers simulated above, the driver model shows excellent stability and convergence characteristics. From a mathematical and control-theoretic point of view, any other maneuver is expected to exhibit similar characteristics. Physiological driver limitations and some vehicle constraints are incorporated into the model, and the dynamics of the vehicle

can be made as complex as necessary for the maneuver of interest through the open architecture of HVE.

3. The use of a dynamically calculated preview distance is an improvement over a static, user-entered value because the preview distance varies with speed. This approach better models the human operator (driver): As a driver, it is natural to adjust preview distance based on speed in a reasonable linear manner. Obviously, different drivers will have differing preview time constraints, $\tau_{preview}$, but this can be accommodated in the model.

4. The HVE Driver Model has several applications useful to the motor vehicle safety industry, including the study of driver response to unexpected events (tire blow-out is an example used in this paper) and the study of driving while intoxicated.

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Reviewer’s Discussion
By David W. Sallmann, Rudny and Sallmann Engineering
SAE # 2000-01-1313
The Simulation of Driver Steering Inputs Using a Vehicle Driver Model
Terry D. Day, L. Daniel Metz, Authors

This HVE Driver Model can be a useful tool to the accident reconstructionist. Open-loop single vehicle simulation models have helped accident reconstructionists to better understand pre-impact vehicle dynamics and driver response to hazards. This model can potentially save a considerable amount of time when performing such analyses. The HVE driver model appears to be easy to use and stable. Compared to previously developed models described in the paper, this model looks simpler and more intuitive. Until the model becomes more widely used, its potential, user friendliness and weaknesses cannot be fully evaluated.

I believe that some of the input parameters need to be further documented through field testing to provide the user with confidence in the applicable range of values. I agree with the authors that this model should be extended to include the throttle and braking inputs required to follow the defined path.

Reviewer’s Discussion
By Donald F. Rudny, Rudny & Sallmann Engineering
SAE # 2000-01-1313
The Simulation of Driver Steering Inputs Using a Vehicle Driver Model
Terry D. Day, L. Daniel Metz, Authors

Anyone who has ever used the open loop method of modeling driver inputs of steering and braking to simulate precise vehicle movement will appreciate the vehicle driver model. The model not only saves time by eliminating seemingly endless iterations, but also establishes an acceptable basis for human response variables. The ability to vary the driver physiological characteristics allows the user latitude in evaluating the effects of driver impairment or physical condition.

It appears that the driver model can be a useful tool in pre-collision reconstruction analysis and study of driver behavior. As the article points out, care should be taken in utilizing the driver model only in stable, near steady-state conditions. It does not appear the driver model will be of use in post impact or loss of control vehicle dynamics.