SIMULATOR STUDIES OF THE DRIVER'S DYNAMIC RESPONSE IN STEERING CONTROL TASKS

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The UCLA driving simulator featuring moving model landscape and TV-projected roadway image has been used to study driver steering control in overtaking and passing maneuvers and random gust regulation tasks. The driver is seated in a car mounted on a chassis dynamometer whose speed determines the landscape velocity relative to the camera. The driver's steering output is fed to an analog computer that contains the vehicle equations of motion, and its parameters define the vehicle's handling properties. The camera has lateral position and heading degrees of freedom corresponding to motions of the subject vehicle. Comparisons with published field data verify that the simulator evokes similar control response from the same driver subjects in equivalent tasks, confirming the realism and utility of the simulator. The experimental series that was reported involved driver steering control to regulate the car during random-appearing crosswind gusts and to maintain the car in the center of the lane on a tangent roadway. The dynamic response properties of 5 driver subjects were measured as quasi-linear describing functions. Although the data are exploratory, they do show fairly consistent values of driver time delay and control response bandwidth across subjects and good repeatability within subjects on successive runs. The data are consistent with previously published models for driver steering control, and they provide some insight into the perceptual feedback structure that the driver may be using.

•RECENT EXPERIMENTAL STUDIES using the UCLA driving simulator show the validity of simulator results relative to field studies and provide an estimate of the driver's dynamic response in random input steering tasks. This paper describes the TV-projected model landscape driving simulator and presents experimental measures of driver-vehicle system response. Emphasis is placed on driver steering control of passenger vehicles on 2-lane rural roads. Simulated tasks included overtaking and passing maneuvers and regulation during crosswind gusts. By mechanizing the vehicle's equations of motion on an analog computer, a broad range of vehicle handling can be simulated by adjusting the dynamic coefficients.

Simulation is useful in driving research because limiting, critical situations can be studied safely; controlled conditions can be created; and task variables can be changed systematically. Typical practice (1, 2, 3, 4, 5) generates the visual field image with closed-circuit TV on scale models, point light source shadowgram, preprogrammed film, and computer generation of roadway abstraction. The driver's station generally consists of a mockup of seat, controls, instrument panels, and windshield display. It is usually a fixed-base device, although simple moving-base devices have been used

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with limited success. Common deficiencies include inadequate visual field size, framing, and reference points to indicate orientation of the driver or vehicle in the external world; lack of realistic vehicle response as reflected in the movement of the displayed cues; and improper steering feel and deficient self-centering properties. These deficiencies can be particularly troublesome in the study of steering control and vehicle handling tasks.

The newly developed simulator at UCLA tries to overcome some of these shortcomings. Its description constitutes the next section of this paper. More details of its construction are given elsewhere (1). In the remainder of the paper, some exploratory results of the describing function are given for driver response with simulated random-appearing crosswind gusts.

SIMULATOR DESCRIPTION

The driver is seated in a 1965 Chevrolet sedan mounted on a chassis dynamometer facing the TV projection screen. A separate room contains the analog computer, a 1:72 scale model landscape, TV camera servo, and associated recording equipment. The setup is shown in Figure 1.

The functional block diagram is shown in Figure 2. The analog computer is an EAI model TR-20. It contains the coupled lateral-directional equations of motion for the car, which are summarized in the Appendix, and provides heading rate and inertial lateral velocity signals to the 2 camera servos. Driver steering actions are fed to the analog computer, and the vehicle handling properties can be modified by changing the dynamic coefficients. Forward speed is controlled by the motion of the model landscape, slaved to the chassis dynamometer. The basic variables, as shown in Figure 2, use the notations given elsewhere (6, 7). Table 1 gives these notations, the units commonly used, and the range of the variables expected during simulator operation.

Although the simulator is a fixed-base type, the vibration of the rear wheels on the dynamometer provides tactile sensation that varies with speed. The car contains conventional power steering, and the front wheels are mounted on spring-restrained swiveling turntables to provide fairly realistic feel and self-centering properties. The self-centering properties are not perfect, however, and there is some hysteresis that the driver must remove to avoid drifts. The speedometer displays twice the actual rear wheel speed (the landscape belt speed is doubled accordingly) in order to maintain road noise at a realistic level. This very approximately doubles the available acceleration rate at any given speed and gives a sensitive throttle response.

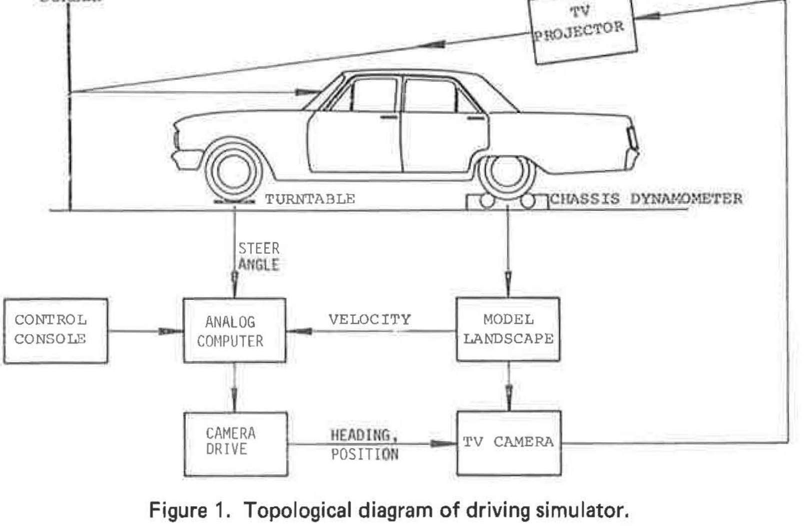

Figure 1. Topological diagram of driving simulator.

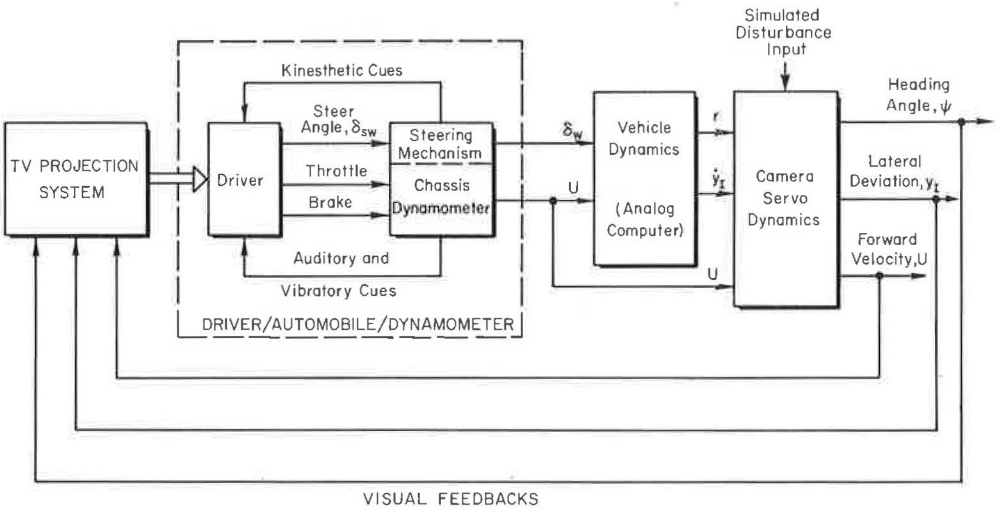

Figure 2. Overall functional block diagram.

The TV camera is a black-and-white GPL Model 1000, with up to 1,000 lines of horizontal resolution, 15 MH_z bandwidth, and a scan rate of 525 lines per frame. The camera lens is an f 2.0 Schneider Xenon with a 16-mm focal length, operating through two 1.5-in. silvered prisms to lower the optical axis to 0.75 in. (equivalent to a full-scale eye height of 48 in.). The TV projector is a Prizomatic 5XTP that is mounted directly above the vehicle. It has a fixed orientation. The included horizontal angle of the visual field is about 40 deg, and the driver is seated relative to the projected image in correspondence to the camera image. The streamer and geometric cues used for directional control are strong and seem adequate for foveal and parafoveal vision. The resolution of the projected image is such that an object the size of an oncoming vehicle can be distinguished as present (if not identified) at an equivalent full-scale distance of about ¼ mile (the length of the moving belt landscape). The overall impression is one of driving in desert terrain under a heavy, dark overcast. After familiarization, the subjects reported that it seemed very realistic. A typical projected scene as viewed by the driver is shown in Figure 3.

Provision is also made to control and measure the position of lead and oncoming cars relative to the subject vehicle. These other vehicles are fixed to tapes (roadway lanes) that move in relation to the model landscape. This is shown in Figure 4, together with the TV camera mount.

The lack of motion cues always has at least a minor effect on a fixed-base simulation of this type. In driving maneuvers and disturbance regulation, the lateral acceleration motion cue provides a useful high-frequency (rapid) cue that alerts the driver to an input onset and provides feedback regarding the initial results of his steering response. Without vestibular cues the driver must wait until the change in the visual display exceeds the threshold, and this delay is increased by any camera servo deadband. The net effect can be treated as an increase in the driver's effective time delay, and this results in reduced performance potential. In this simulation the effect does not appear to be significant. This is confirmed by the experimental results (1),

TABLE 1

DEFINITION OF SIMULATION VARIABLES

Variable	Notation	Range
Forward velocity, ft/sec	U or U_o	0 to 100
Steer angle, rad	δ_w	±0.2
Heading angle, rad	ψ	±0.2
Heading rate, rad/sec	r	±0.3
Lateral acceleration, g	a_y	±0.3
Lateral velocity, ft/sec	v	±10
Inertial lateral velocity, ft/sec	$\dot{y}_I$	±20
Lateral deviation, ft	y_I	±20

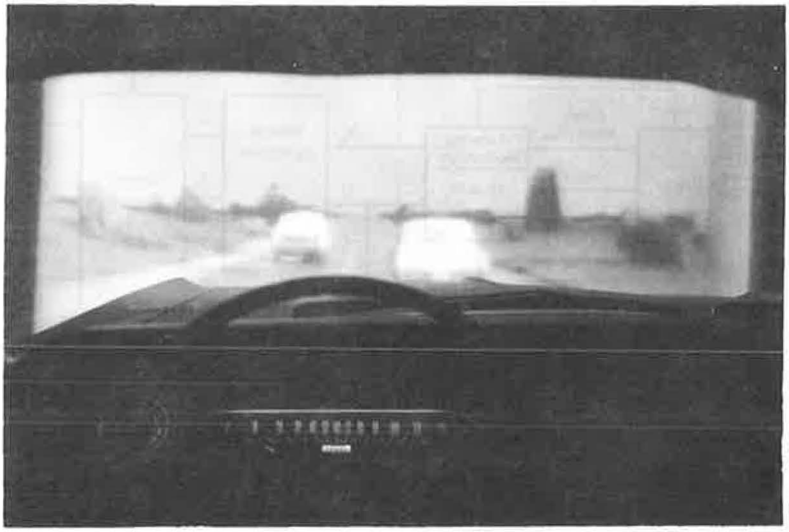

Figure 3. Road scene as viewed by driver.

which show good comparison between field and simulator results for the same tasks and subjects.

SIMULATED VEHICLE DYNAMIC RESPONSE

Several vehicles with different handling properties have been simulated to date. The one used in the experiments reported here was a nominally loaded full-sized station wagon with less than ideal handling properties.

The assumed design parameters and vehicle stability derivatives are given in Table 2 and use the notations given in the Appendix. Substituting these stability derivatives into the lateral-directional equations of motion and rearranging give the following vehicle-motion-to-steer-angle input transfer functions:

Lateral velocity

$$\frac{v}{\delta_w} = \frac{91(s - 16.4)}{s^2 + 2(0.79)(3.3)s + (3.3)^2} \quad (1)$$

Heading rate

$$\frac{r}{\delta_w} = \frac{19.5(s + 2.8)}{s^2 + 2(0.79)(3.3)s + (3.3)^2} \quad (2)$$

Lateral deviation (position in lane)

$$\frac{y_l}{\delta_w} = \frac{91[s^2 + 2(0.19)(7.4)s + (7.4)^2]}{s^2[s^2 + 2(0.79)(3.3)s + (3.3)^2]} \quad (3)$$

The dynamic response properties are sim-

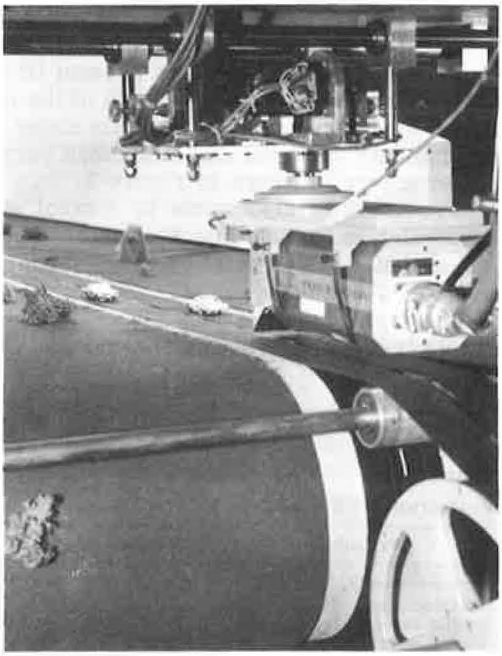

Figure 4. TV camera, other vehicles, and model landscape.

ilar to those of the test vehicle used in prior field experiments (8).

The analog computer diagram is shown in Figure 5. The kinematic variation of speed in the equations (i.e., the $U\Psi$ term) was accounted for by using the speed sensed by a belt-driven tach-generator. Some of the stability derivatives (Y_v, Y_r, N_v, and N_r) are inversely proportional to speed in the nominal driving range (45 to 60 mph); however, fixed settings corresponding to 60 mph were used for simplicity. Where possible, the experimental tasks were planned for a constant 60 mph. Operation at speeds below the design values results in a less responsive vehicle than would normally be the case if the derivatives were speed varying (6).

TABLE 2

DYNAMIC PARAMETERS FOR SIMULATED CAR

Design Parameters		Stability Derivatives	
Notation	Amount	Notation	Amount
m (slugs)	151	Y_v (sec^{-1})	-2.8
U_o (ft/sec)	88	Y_r (ft/sec-rad)	1.33
Y_{α_1} (lb/rad)	6,860	N_v (rad/ft-sec)	0.05
Y_{α_2} (lb/rad)	11,700	N_r (sec^{-1})	-2.45
a (ft)	5.77	Y_{δ_w} (ft/sec^2-rad)	91
b (ft)	4.14	N_{δ_w} (sec^{-2})	19.5
I_{zz} (slug-ft^2)	4,060	N_{v_g} (rad/ft-sec)	-0.003
ℓ (ft)	9.91	Y_{v_g} (sec^{-1})	-0.035

Although the analog computer provides a good representation of the vehicle steering response, the camera servo drive for heading has a small amount of backlash that results in a deadband and hysteresis. The magnitude of the deadband is less than a degree, but it may be important for small heading corrections and accurate disturbance error regulation.

OVERTAKING AND PASSING EXPERIMENTS

A major objective of the overall research study was to replicate full-scale field measurements of driver control for simulator validation. Previously published response and performance measurements for overtaking and passing tasks with and without an

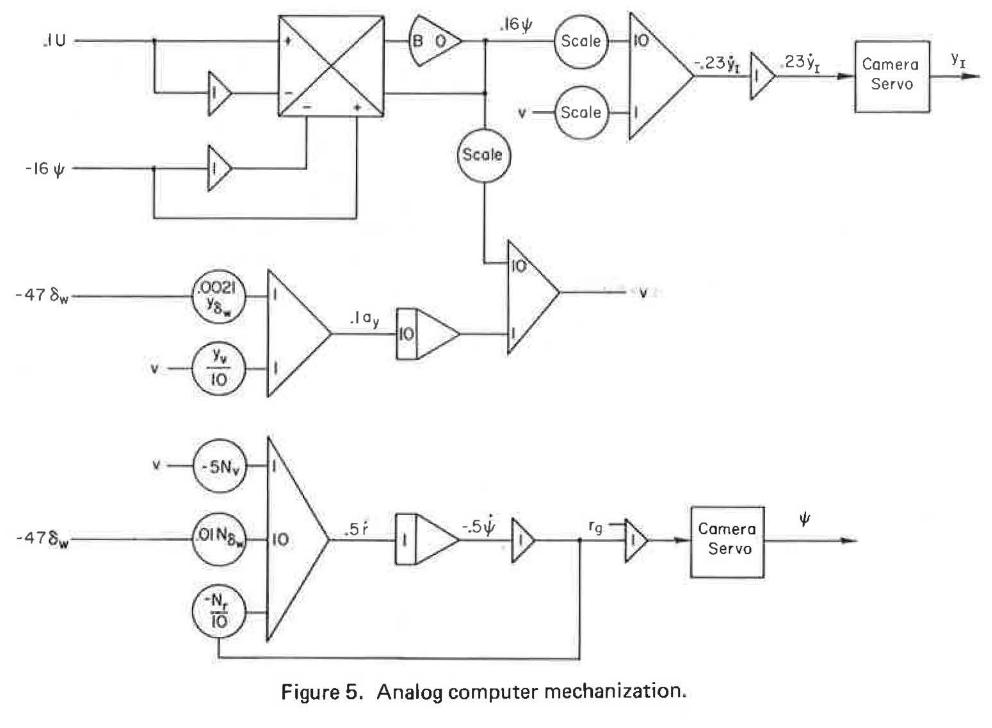

Figure 5. Analog computer mechanization.

oncoming vehicle (8) provided a useful field database. These tasks were repeated in the simulator by the same driver subjects so that at least some subjects served as their own controls. If transfer effects are negligible, any differences for these subjects would be due to physical effects such as lack of vestibular cues, degree of visual realism, and differences in handling dynamics.

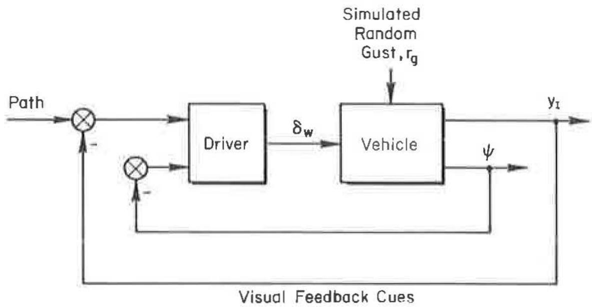

Figure 6. Driver control loops.

Details of these experiments are given elsewhere (1). To summarize, the simulator results were in good agreement with the previously published field data (6) for comparable tasks. The same relative changes occurred in field and simulator as the tasks changed. With comparable controlled element dynamics and the same driver subject, both the absolute levels of driver-vehicle response in a given task and the magnitudes of the change between situations were quite similar in field and simulator. These results confirmed the validity of the simulator task with respect to evoked response and performance.

RANDOM CROSSWIND GUST EXPERIMENTS

In contrast to overtaking and passing, continuous closed-loop operation by the driver dominates in the presence of a random-appearing disturbance input such as a crosswind gust. With continuous control, on-the-average frequency response properties of the driver can be measured as a describing function.

Models for the driver in continuous control task have been described previously (7, 9). Several feedbacks such as heading angle or rate and path angle or rate were shown to be good "inner loop" control cues, while a necessary "outer loop" for trim control seems to be lateral deviation in the lane. With a dynamic simulator of the sort used in the experiments it is possible to structure regulation tasks and measure the driver's response under the interpretation that certain feedbacks are dominant; and this is accomplished as described in the following. Investigation of the more fundamental question of which feedback structures are operant in a given driving situation requires extension of these experimental techniques, and has yet to be accomplished.

These experiments were set up so that the driver's steering response resulted from his operation on heading angle, Ψ, and lateral deviation, y_I, cues. The multiloop block diagram shown in Figure 6 for this case is the simplified version of the diagram shown in Figure 2. The driver's task is to maintain the car in the center of the lane (at 60 mph) in the presence of the equivalent crosswind gust signal.

Because only 1 gust input is being used, the analyses concentrated on the middle- and high-frequency driver response data that are dominated by the heading disturbance in this task. Then the lateral deviation outer loop is assumed to result in low-frequency corrections to reduce errors that accumulate despite the driver's attempting to maintain the car heading parallel with the roadway. The fidelity of the measurements is reflected in the linear correlation in the data between the disturbance input and the driver's steering response, as measured by ρ_ϵ^2.

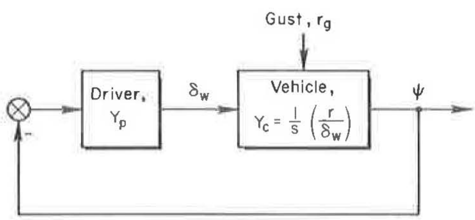

Figure 7. Simplified system for data interpretation.

With this interpretation, the driver-vehicle system takes the single-loop form shown in Figure 7, which accounts for the dominant characteristics in this task. The vehicle's dynamics, Y_c, are given by integrating the heading rate to steer-angle transfer function in Eq. 2, and the result is approximately a simple integration or K/s controlled element; i.e.,

$$Y_c = \frac{\Psi}{\delta_w} = \frac{1}{s}\left(\frac{r}{\delta_w}\right) \rightarrow \frac{K_c}{s} \tag{4}$$

In this case, the driver model, Y_p, takes the form of a pure gain plus time delay, as follows:

$$Y_p = \frac{\delta_w}{\Psi_e} = K_p e^{-\tau_e j\omega} \tag{5}$$

as shown elsewhere (7, 9). The complex frequency, $j\omega$, is used (instead of s) in the driver-describing function because the describing function is computed by taking the ratio of cross spectra that are Fourier transforms.

The heading rate gust disturbance signal, r_g, was a random-appearing sum of equal amplitude sine waves with component frequencies at 0.5, 1.26, 3.0, and 6.3 rad/sec, and an rms amplitude of 1.8 deg/sec. The camera servo acted as an integrator that produced a heading angle disturbance that rolled off at 20 dB/decade, as if low-pass filtered. The resulting heading angle disturbance appeared to have a bandwidth of about 0.7 to 1.0 rad/sec on the display, with an rms amplitude of approximately 1.7 deg. The subjective effect is not unlike that of driving a very gust-sensitive car in an intermittent crosswind.

DRIVER-DESCRIBING FUNCTION DATA

The driver model (7) provides for his equalization of the vehicle dynamics such that the combined driver-vehicle system properties are approximately invariant. The result is that the driver-vehicle describing function for closed-loop operation on a displayed cue has the general form

$$\frac{\Psi}{\Psi_e} = Y_p Y_c \rightarrow \frac{\omega_c}{j\omega} e^{-(\tau_e j\omega + \alpha/j\omega)} \tag{6}$$

TABLE 3
SUBJECT BACKGROUND

Subject	Age	Years Driving	Personal Vehicle	Passes on Rural Roads: Last Month	Passes on Rural Roads: Last Year	Remarks on Simulator Realism
B	48	18	1962 Mercury Comet	0	10	—
C	23	7	1969 Ford Econoline Van	—	—	Steering was oversensitive; simulation seemed OK for cues.
D	34	18	1965 Ford Mustang; 1969 VW squareback	15	50	Vehicle response was realistic; it was easy to project oneself into task so that lack of visual field acuity and limited peripheral cues are not noticed. Lateral acceleration cues are missed in first fraction of second following steering inputs.
E	30	14	1968 Volvo 144	0	20	Visual scene was like heavy overcast with light rain. Some ill effects were due to lack of motion cues. Vehicle seemed somewhat oversensitive and gusts were too lively. Considering limitations, however, simulator seemed surprisingly realistic.
F	30	13	1964 Buick station wagon; 1968 Karman Ghia	10	30	Could not judge center of lane well. Vehicle 2 handled naturally. Visual scene was like light snow condition.

where Y_p is the driver and Y_c is the controlled element. The parameter ω_c is the Bode crossover frequency (or closed-loop system gain) and provides a good estimate of the driver-vehicle system bandwidth. The effective time delay is τ_e as shown in Eq. 5. The additional parameter, α, accounts for the driver's low-frequency phase lag (often attributed to his neuromuscular properties).

The output to error describing the function of Eq. 6 was measured directly on-line by using the describing function analyzer (DFA), Systems Technology, Inc., model 1001. This DFA also supplies the random-appearing heading rate disturbance input described previously. The driver-describing function, Y_p, is computed from Ψ/Ψ_e by dividing by the assumed vehicle dynamics or controlled element, $Y_c = \Psi/\delta_w$. Each experimental run lasted 100 sec.

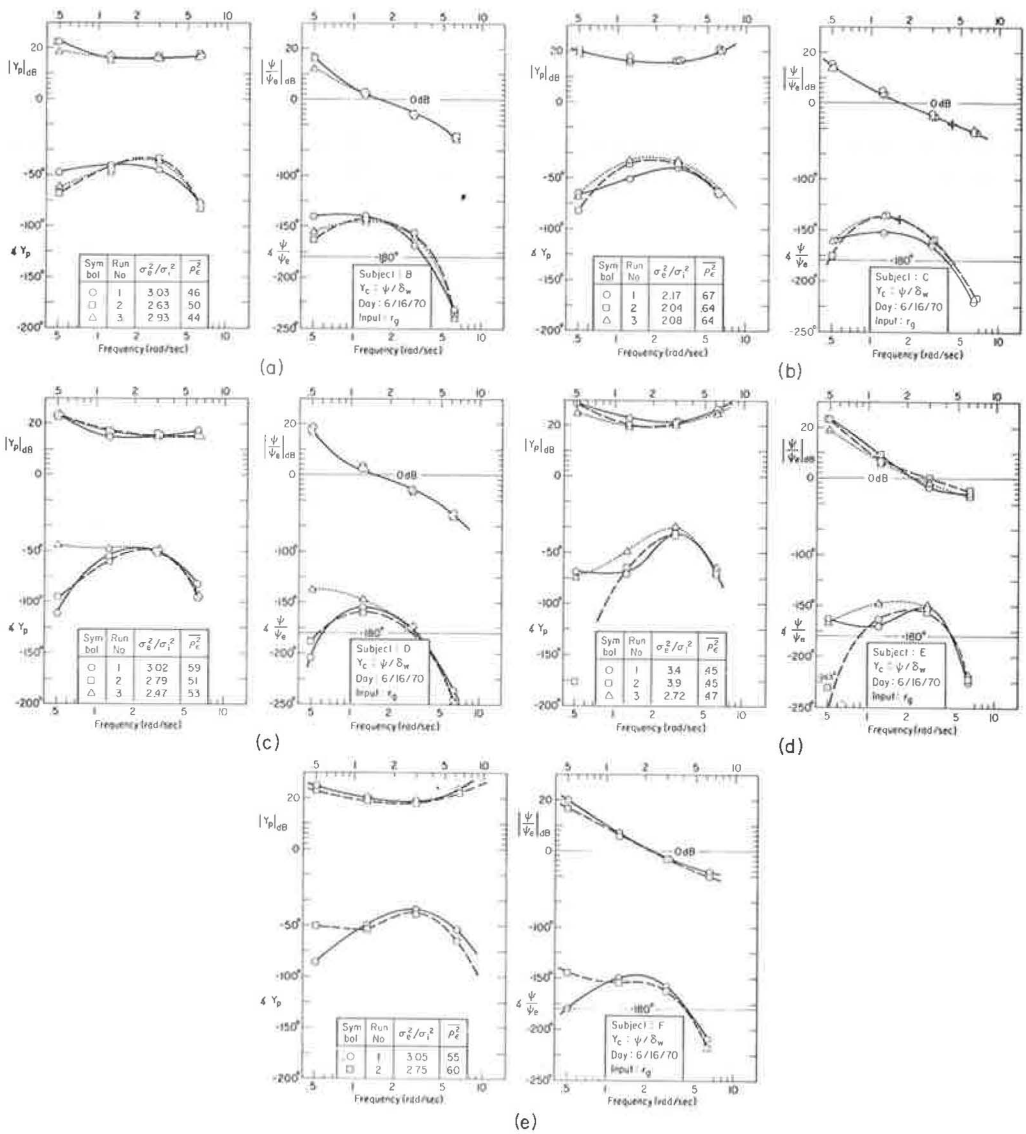

Figure 8. Individual subject-describing function data.

TABLE 4

SUMMARY OF DESCRIBING FUNCTION RESULTS

Subject	ω_c (rad/sec)	φ_m (deg)	G_m (dB)	τ_e (sec)	ω_u (rad/sec)	ρ_ϵ^2
B	1.7	35	8.3	0.34	3.8	0.47
C	1.8	36	7.5	0.35	4.1	0.65
D	1.7	24	6.9	0.41	3.3	0.54
E	2.9	27	2.9	0.24	4.3	0.46
F	2.3	28	5.6	0.32	4.3	0.58

Estimates of driver-vehicle model parameters given in Eq. 6 have been made by using the DFA results for several runs on each of 5 driver subjects whose backgrounds are given in Table 3. The individual data runs are shown in Figure 8, with Y_pY_c on the right and the computed Y_p on the left. The averaged parameters for the fitted curves are given in Table 4. Also given in Table 4 are the closed-loop phase margin, φ_m, gain margin, G_M, and zero phase margin crossover frequency, ω_u, which relate to system stability and the quality of control. The average linear correlation, $\overline{\rho_\epsilon^2}$, is the fraction of the total heading rate error that is linearly correlated with the gust input—the average coherence. Values in the range of 0.5 to 0.6 indicate that the majority of the driver's steering actions are heading angle or heading rate corrections that are correlated with the gust input, and these values are consistent with prior instrument display data. The ratio of σ_e^2/σ_i^2 is the total heading rate error variance over the total heading rate input (r_g) variance, and the larger values shown in Figure 8 may imply that the driver is using a low-frequency heading bias to correct residual errors in lateral deviation (Fig. 6).

The dominant features of the data are the consistent similarity in crossover frequency, effective time delay, and stability margins. This is true not only for one subject (as expected) but also for all subjects. The crossover frequency is bounded on the low side by the gust bandwidth in which the former has to be nearly twice the latter to achieve effective control (9). Crossover frequency is limited on the upper side by the effective time delay (due to driver and car) and stability considerations. The repeatability in the data is associated with these task-related constraints.

The measured driver-response properties and stability margins are compatible with inner-loop crossover frequency predictions made for similar vehicle-task situations in prior studies (7, 8), implying strongly that heading angle is a reasonable inner-loop cue in the multiloop driver-vehicle system structure. Lagged heading rate is a reasonable alternative, but simple proportional operation on (unlagged) heading rate is not a compatible alternative because (a) it is inconsistent with the previously noted form of Y_pY_c based on a large body of prior data and (b) the effective gust bandwidth of 6.3 rad/sec would then be prohibitively large. Finally, the observed values of τ_e and φ_m are more consistent with prior data for $Y_c = K/s$ (i.e., heading angle) than for $Y_c = K$ (i.e., heading rate).

The peaking up of the high-frequency amplitude ratio for subjects C, E, and F (Figs. 8b, 8d, and 8e) indicates that they are using lead equalization to offset the additional high-frequency lag in the simulated car. The result is given in Table 4 as a lower effective time delay, which in turn permits a higher crossover frequency (with the same stability margins) and better gust-regulation performance. The stability margins for each driver are large enough to give smooth (comfortable) response, as well as rapid error reduction. The α measures are somewhat unreliable because they represent a least squares fit to only the middle 2 frequency points.

These exploratory data show that repeatable measures of driver response in closed-loop steering control tasks can be made. Not unexpectedly, the results are consistent with predictions from prior (empirically derived) driver-vehicle models, and they provide added insight into the multiloop feedback structure that the human operator may adopt when provided with a cue-rich, real-world visual field.

CONCLUSIONS AND IMPLICATIONS

A major objective was to implement and exercise a driving simulator useful in the study of driver control processes and to establish the validity of simulation results by comparison with published field data for similar subjects and tasks. This has been accomplished. The dynamic response and performance of the simulator are subjectively realistic, and data yielded by the simulator are similar to field data. The simulator data also show the same sensitivity to variations in tasks and conditions as do the field data. By mechanizing the vehicle's differential equations on an analog computer, a broad range of vehicles can be simulated by simply adjusting dynamic coefficients.

Driver-describing functions have been measured in a simulated crosswind gust regulation task. These exploratory results were repeatable and compatible with existing driver-vehicle system models. The numerical parameters confirmed prior estimates of closed-loop properties and provided new insight to the possible driver-vehicle system multiloop structure.

These analyses and data confirm that the UCLA driving simulator using a model-landscape TV display is an effective applied research tool and that it is useful in the study of a broad range of driving tasks and potentially hazardous situations.

ACKNOWLEDGMENTS

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APPENDIX

LATERAL-DIRECTIONAL VEHICLE DYNAMICS

The lateral motions of a car, which dominate in steering control and are represented in the simulator system, are shown in Figure 9. The defined symbols are given in Table 1.

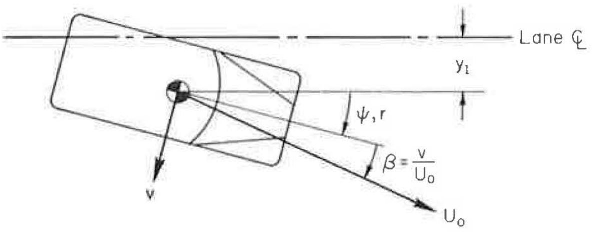

Figure 9. Motion quantities for directional control.

The lateral-directional matrix equation for a car with lateral velocity, v, and heading rate, r, is summarized in Eq. 7 as follows [degrees of freedom are derived elsewhere (6)]:

$$\begin{bmatrix} s - Y_v & U_o - Y_r \\ -N_v & s - N_r \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} = \begin{bmatrix} Y_{\delta_w} \\ N_{\delta_w} \end{bmatrix} \delta_w + \begin{bmatrix} Y_{v_g} \\ N_{v_g} \end{bmatrix} v_g \qquad (7)$$

where s is the Laplace transform complex variable. The front wheel steer angle is δ_w, and v_g is a lateral velocity gust. The stability derivatives are defined in terms of vehicle and tire design parameters by the following expressions:

$$Y_v = \frac{-2}{mU_o}\left(Y_{\alpha_1} + Y_{\alpha_2}\right) \qquad Y_{\delta_w} = \frac{2}{m} Y_{\alpha_1}$$

$$Y_r = \frac{2}{mU_o}\left(bY_{\alpha_2} - aY_{\alpha_1}\right) \qquad N_{\delta_w} = \frac{2a}{I_{zz}} Y_{\alpha_1}$$

$$N_v = \frac{2}{I_{zz}U_o}\left(bY_{\alpha_2} - aY_{\alpha_1}\right) \qquad Y_{v_g} = \frac{qA}{mU_o} C_{y_{\beta_g}}$$

$$N_r = \frac{-2}{I_{zz}U_o}\left(a^2Y_{\alpha_1} + b^2Y_{\alpha_2}\right) \qquad N_{v_g} = \frac{qA\ell}{I_{zz}U_o} C_{n_{\beta_g}}$$

The design parameters on the right of these equations are defined as follows: m is the total vehicle mass; U_o is the nominal forward velocity; Y_{α_1} is the side force due to front tire slip angle; Y_{α_2} is the side force due to rear tire slip angle; a is the distance of the center of gravity aft of the front axle; b is the distance of the center of gravity aft of the rear axle; I_{zz} is the total vehicle yaw moment of inertia; q is the aerodynamic pressure; A is the projected frontal area; $\ell = a + b$ and is the wheel base; and $C_{y_{\beta_g}}$ and $C_{n_{\beta_g}}$ are the aerodynamic coefficients. More detailed descriptions are given by Weir, Shortwell, and Johnson (6).

Normally Y_r is much less than U_o. Another simplification shown in Eq. 7 is the deletion of the gust terms, Y_{v_g} and N_{v_g}, from the left side because they are small relative to the tire forces and moments, Y_v and N_v, at reasonable speeds. They are included on the right side to provide for force and moment disturbance inputs to the simulation.

These equations dealing with 2 degrees of freedom do not include the roll mode. It can have considerable influence on them by modifying the effective Y_{α_1} and Y_{α_2}, mainly because of roll steer and camber thrust effects. Knowledge of the complete equations dealing with 3 degrees of freedom and complete data allows this correction to be made in the model dealing with 2 degrees of freedom. Another result of including a roll degree of freedom is the appearance of a usually inconsequential high-frequency dipole pair in the lateral-directional transfer functions. Hence, the equations dealing with 2 degrees of freedom that were used in the simulation reflect the major effects of the roll mode without including it explicitly.

DISCUSSION

Howard Dugoff, U.S. Army Tank-Automotive Command, Warren, Michigan

The paper by Weir and Wojcik represents impressive engineering achievements in the hardware and software specialties for which the authors and their respective organizations have already earned wide and well-deserved reputations. My discussion is concerned not only with the engineering aspects of the work but also with the implications or, more precisely, with the implications that the authors attribute to it. Like most discussants, I am going to talk less about what the investigators did do than about what they did not do.

I want to make a couple of points with regard to specific features of the simulation. First, the simulator is configured to provide "double the acceleration rate at any speed," which I interpret to mean double the actual acceleration rate of the simulated vehicle on the road. Because the apparatus is being used to investigate passing maneuvers that do involve acceleration, this seems to be an extremely undesirable characteristic. Would it not be both feasible and worthwhile to program the chassis dynamometer so that not only the road noise is kept to a realistic level but also the vehicle performance characteristics are accurately simulated?

Second, kinesthetic feedback at the simulator steering wheel is produced by mounting the simulator vehicle's front wheels on spring-restrained turntables. This expedient results in steering wheel torques that are proportional to steer angle. But aligning torques in real vehicles are functions of tire sideslip angles and not steer angles. Even in the linear motion regime, for which the simulator is basically designed, there can be significant differences between steer angles and sideslip angles, particularly in lane-change maneuvers or maneuvers under wind gust loadings. In fact, one of the principal mechanisms whereby wind loadings perturb the real-world driving process is through the steering wheel feedback, which is not modeled in this simulation. Given that one of the principal program objectives was to produce a simulation with steering feedback characteristics that would overcome deficiencies found in past simulations, particular efforts to eliminate this infidelity would appear to be warranted. I would speculate that an active system for accurately simulating steering feedback effects could be put together reasonably cheaply by using an electrohydraulic servo system in conjunction with a minimal amount of analog-computing equipment.

The authors have demonstrated strong similarities between the performance of subjects in simulated driving and the performance of subjects in real-world driving. I am very impressed by this finding, particularly for the passing maneuvers, where I would have predicted that the absence of lateral and rearward visual displays would have resulted in extremely unrealistic performance. This similarity and the generally high degree of face validity of the simulation certainly suggest that the new simulator might be a useful tool for studying particular aspects of the driving process. As to its potential utility for the study of really hazardous situations, we cannot say as much.

I do not believe that many accidents occur as a result of driver inadequacy in the continuous, psychomotor aspects of course-keeping. I think that many accidents do occur as the result of distinct blunders or lapses in the perceptual or judgmental aspects of the process.

We need studies that will tell us why a driver decides to pull out and pass in the face of an oncoming truck and not what trajectory his vehicle will follow before it collides with the truck. Accordingly, I would like to see Weir and Wojcik focus their formidable experimental and analytical methodology specifically on the study of how the driver perceives and processes information, rather than on the mechanisms of how he translates the processed information into performance of the driver-vehicle system.

Phyllis E. Huntington, Federal Highway Administration,
U.S. Department of Transportation

The simulator described in the paper was developed for the purpose of studying driver control on 2-lane roads under various traffic and environmental conditions. Experimental simulator studies were conducted to show the validity of the simulator results when compared with the results of field studies for the same tasks and situations. In the field studies, the driver's tasks were those of overtaking and passing under various conditions that are described adequately in the paper. It was expected that the validation by comparison effort would result in quantitative measures of the degree of similarity between the simulator and the real world for the tasks specified. My comments are directed at the discussion of the validation effort presented in the paper.

The validation discussions centered on time history comparisons of the experimental variables of steer angle, measured at the front wheels of the vehicle, and lateral deviation. Other time histories from the field studies were available but were not shown. It is inferred from the paper that these other experimental variables were compared with the simulator data and are, in the authors' words, "comparable."

The discussion of the time history comparisons are the only means for this discussant to conclude, along with the researchers, that the validity of the simulator task with respect to evoked driver response and performance has been confirmed. It is not clear whether there is a figure of merit that should be applied to the simulator results to provide some means for determining the limitations of utilizing the simulator for measuring driver control responses related to other control tasks.

The same subject who produced the time histories for the field data was used as a subject in the performance of the validating simulator studies. It could be assumed that this expert subject would inject less variability in the performance of the same tasks and would therefore provide the best data for determining the degree of similarity between the simulator and the real world. Several subjects were used for determining the effect of changing the experimental design, i.e., the simulation. This occurred only after the researchers had established that the simulator had been, for all intents and purposes, validated. The question raised here is whether it is possible to accept the results of a single biased subject for establishing validity.

Eugene Pazera, U.S. Public Health Service

I am encouraged to find that at least a few people are able to remain concerned with or to have the financial support to continue in the field of general-purpose, full-task driving simulation development or to do both of these. Our own interests in driver behavior under the influence of drugs and alcohol preclude field studies for reasons of safety. The dearth of activity toward definition of minimum requirements and standards for and development of methods for implementation of full driving-task simulation offers little hope for sorely needed technological breakthroughs until greater concern, priority, and effort are applied in this direction.

At one end of the spectrum we have complex computer modeling of vehicle dynamics and characteristics that, for the most part, exclude a real driver. At the other end, because of apparent technological limitations, we have a proliferation of part-task driving simulators such as our own, with rudimentary analogs of normally cue-rich visual scenes and often empirically derived control loops assembled to attach specific research problems. Often the research problem must be compromised to suit the limitations of the testing facility. It is not my intention to denigrate the latter because, with proper experimental control, they have been and will continue to be extremely useful in behavioral research in driving performance. We are continually plagued, however, with their limitations and the desire for study of more complex system interactions that require higher fidelity simulation. To approach the goal of a generally useful research tool at reasonable cost, we must first define the active interrelationships among driver, vehicle, and environment and establish minimum standards of performance.

It is in this area that I think this paper is most significant—that is, the methodology of control theory in measurement of driver-simulator interactions for validation of simulator improvements and quantitative determination of the level of driver sensitivity to signal input in a specific control loop. Extension of this method to other elements of the driving task should be encouraged. It is needed for definitive determination of relative dominance of various signal input channels in real-world multiloop structures or of their absence in the simulated environment. Then the simulation can be structured, in the first case, without costly redundancy and with possible avoidance of technological barriers and, in the latter case, with cues of at least minimum efficacy present to ensure valid overall task simulation.

The use of time-history analysis in the comparison of field and simulator passing maneuvers appears to offer face validity for the selected vehicle steering dynamics. A word of caution is appropriate, however, because the driver is an extremely adaptable creature. Unless submitted to appropriate stress in the simulation, he is subject to participation in a form of gamesmanship, responding in a normally expected manner in spite of abnormal or inappropriate simulator design characteristics. This was found to be true with one of our simulators in which the steering angle input was directly proportional to lateral velocity rather than to rate. None of our subject drivers has ever expressed an awareness of the difference nor shown performance differing substantially from normally expected behavior. This suggests that the quality of simulation need not in all cases fully replicate the real world to achieve a goal. In our own empirical experience, for example, design effort toward high-fidelity sound appears less significant than provision of accurate somesthetic feedback in the form of steering wheel and floor pan shakers. Similarly, we may not need complex and costly moving bases to replicate acceleration cues once we have determined the character of the driver's response to such feedback. It may only be qualitative in nature, and rudimentary presence may be adequate for simulation.

A considerable amount of work—and much more support—is needed to further the quality of simulation to permit more sophisticated research in driving behavior, particularly in improvement of visual field size and resolution and in introduction of appropriate levels of proprioceptive and somesthetic cues to close control loops associated with braking, curve handling, speed control, and emergency behavior. The authors are to be commended for significant progress in improvement of the UCLA driving simulator, and I hope that their activities in this area will be continued.

AUTHORS' CLOSURE

The discussants' points are well taken, and we appreciate their interest and encouragement. To the questions raised, we offer these brief closing remarks.

With regard to Dugoff's discussion, these comments can be made. The available acceleration was unusually large (for a standard station wagon) in the 50- to 60-mph speed range, but the subject drivers soon learned to use an appropriate level of performance that was less than the maximum available throttle control.

Providing high-fidelity kinesthetic feedback can be a difficult problem, and to do it properly with an unassisted steering system would require a good electrohydraulic force feedback system (or the equivalent). In the UCLA driving simulator the problem is alleviated by the presence of power steering, and the subjective result is realistic.

Driver information acquisition and decision processes are indeed important in the precrash phase of the driving task, and the UCLA simulator is well suited to studies of this kind. In fact, concurrent research programs at UCLA are investigating the effects of various drugs and alcohol on things such as driver decisions, judgments, and attentional workload. Nevertheless, maneuvers and disturbance regulation are involved in nearly all phases of driving, and they can have an important effect on set decision processes, performance with a given environmental disturbance, ability to avoid an imminent collision, and so forth. This is particularly true when the vehicle's handling properties degrade or the input levels increase, resulting in an increase in the driver's workload. The perceptual processes are a central concern in our studies of the driver-vehicle control problem.

With regard to Huntington's discussion, several observations can be made. The previous published field results consisted of transient response measures pertinent to the discrete steering maneuvers that characterize overtaking and passing. While not time-averaged, these transient responses do have quantitative features such as rate of lane change, overshoot in opposite lane, rate of pull-in, and residual oscillations. These features were compared with those of the corresponding simulator data. The specific comparisons were not published because of space limitations, but they are given elsewhere (1).

A figure of merit for evaluating simulators would be very useful. This might be some combination of random and discrete objective tests, parameters of the visual display, and a suitable subjective rating summary. At the same time, there is a great need to define performance measures for use in studying driver control processes and for the general quantification of driver-vehicle safety performance.

Validation of any simulation with corresponding measurements under equivalent full-scale field conditions is difficult to achieve, and one tends to make the most of available resources. In this case we were fortunate to avoid many of the difficulties, even to the extent of using the same driver subjects. This allowed the effect of inter-subject variability to be removed. Insofar as transfer of training effects from field to simulator were not significant, each subject was his own control, and any observed differences would have been due to task differences. This could result from the lack of vestibular cues, changes in the visual field content, or a programmed change in handling dynamics. Because important differences did not occur for the tasks studied, the simulation was deemed to be representative.

Pazera points out that fidelity of the simulation is an important problem, including the amount required with respect to each attribute. This highlights again the very fundamental question of measuring performance. A valid measure should be sensitive to the simulator's properties and the nature of the driver's response. We have shown the describing function to be a sensitive measure of the form of the driver's control response in random input tasks and one that changes with the vehicle's handling properties and available perceptual cues. It is only a partial description in the larger frame that encompasses maneuvers and decision processes and that embodies the overall question of safety performance as it reflects and relates to accident causation.