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Foreword

Transportation authorities are increasing the amount of attention paid to the driver of the vehicles and also to the vehicle itself. What once was taken for granted and believed incapable of change, i. e., the driver, is now being studied as to how his desires, his peculiarities, his approach to driving, and his limitations may be taken into account in better highway design and operations. Similarly, the characteristics of the vehicle have been found to be subject to the onslaught of research and nowadays a better vehicular product can be produced that will result in potentially better highway operations if the parameters of the vehicle are known well enough to be fitted into travelway design.

The seven papers presented in this RECORD report on research aspects of road user and vehicle characteristics. Adding to existing knowledge, they present interesting views on the role of the elements of the driver and the vehicle as both interrelate with the facility. These contributions of psychologists, human factors specialists and vehicle safety experts should be of assistance to facility operators and designers.

The first paper by three Pennsylvania researchers indicates studies made of remedial devices which aid passing maneuvers on two-lane rural roads. The authors ascertained that if drivers could be provided knowledge of oncoming-car speeds or closing rates in the passing situation, they could probably make better and safer decisions as to whether or not to pass. Ultimately, this could have a significant effect on enhancement of safety and throughput.

The second paper describes how two California systems analysts structured an analytical model that described drivers' steering control. Using a simplified system simulation, the researchers evolved mathematical models which are said to give the highway engineer an analytical tool that can determine the role of each system element better (driver, vehicle, roadway), define the interaction between elements, and assess the effect of changing systems of parameters at the preliminary design stage.

Studying the movement of drivers' eyes has long been recognized as desirable, but the techniques of doing so under dynamic driving conditions are indeed difficult! Three Ohio University researchers have set forth a practical method of doing this. Using their stabilization unit, the authors recorded drivers' eye movements under dynamic driving conditions and found that calibration accuracy was comparable to that existing in laboratories where the subject's head is held stationary.

The fourth paper sets forth conclusions reached by two Bureau of Public Roads researchers in comparing drivers' estimate of overtaking and passing distance with actual overtaking distance. The researchers found that drivers' estimates are quite afield from the actual requirements and drivers almost always underestimate actual requirements especially at high speeds. The researchers also developed mathematical expressions that set forth the four basic quantities involved in the overtaking and passing situation.

The fifth and sixth papers are by the Franklin Institute researchers. The first of the two papers is concerned with drivers' ability to make passing judgments in performing a flying pass maneuver. It was found under the controlled environment conditions that the decision on making the pass was based largely on remaining sight distance and that there was a high degree of consistency between drivers on the passing decision. The other paper is concerned with driver judgment in overtaking situations. By experiment, it was found that drivers were able to estimate and take closing rates into account to a limited extent, but tended to dangerously overestimate time headways between their overtaking vehicle and a lead vehicle.

The last paper by two Ford Motor Co. researchers, presents a state-of-the-art report on the safety aspects of vehicle handling. The authors set forth the boundaries of the design parameters needed to be known for safer vehicle handling, taking into account the limitations on human and vehicular performance. The five discussions that accompany this paper attest to its interest and impact and the authors provide a closure that rounds out the technical content of this book.

Contents

Knowledge of Closing Rate Versus Knowledge of Oncoming-Car Speed as Determiners of Driver Passing Behavior

EUGENE FARBER, CARL A. SILVER, and DANIEL LANDIS,
The Franklin Institute Research Laboratories, Philadelphia

Previous work by the authors has established that (a) drivers are unable to make useful discriminations of either oncoming-car speed or closing rate in passing situations on two-lane highways, and (b) providing drivers with knowledge of oncoming-car speed enhances their ability to make valid passing judgments. The purpose of the present research is to compare the utility of providing drivers with knowledge of lead-car/oncoming-car closing rate or of oncoming-car speed in making passing judgments. In controlled experiments on a closed roadway, subjects were required to make passing judgments under three different knowledge conditions: knowledge of oncoming-car speed, knowledge of closing rate, and no knowledge. The major findings were that (a) subjects displayed no ability to discriminate oncoming-car speed; (b) subjects were able to take their own speed into account in deciding when to pass; (c) subjects were able to make effective and accurate use of both closing-rate information and oncoming-car speed information in deciding when to pass; and (d) there were no significant differences between the closing-rate knowledge and oncoming-car speed knowledge conditions. It is recommended that the feasibility of providing drivers with knowledge of the speeds of other vehicles on the highway be explored with respect to its effect on safety.

•PREVIOUS studies of automobile overtaking and passing on two-lane highways have established that drivers cannot judge accurately either oncoming-car speed or closing rate. The purpose of this research was to determine the effect of providing drivers with knowledge of either closing rate or oncoming-car speed in accelerative passing situations on drivers' decisions as to whether or not to pass.

In an accelerative pass, the overtaking driver starts from a close following position, with little or no speed advantage, and accelerates to complete the maneuver. Where the passing opportunity is limited by an oncoming car, the would-be passer must consider his own speed, the speed of the oncoming car, and his distance from the oncoming car to make valid passing decisions, that is, to pass only when it is safe, and never to pass when it is unsafe.

Oncoming-car gap acceptance behavior by drivers has been studied by several authors (1, 2, 7). These papers have been reviewed in detail elsewhere (3); the results indicate that drivers are relatively good judges of distance in passing situations, but poor judges of either closing rate or oncoming-car speed. Similarly, the results of observational studies of passing behavior on two-lane public highways (5) indicate that

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Paper sponsored by Committee on Road User Characteristics and presented at the 47th Annual Meeting.

the passing decision appears to be completely unrelated to oncoming-car speed. Michaels (6) provides a basis for understanding this insensitivity to oncoming-car speed; his data suggest that, at the distance at which most passes take place, the speed cue associated with the rate of change of the visual angle subtended by the oncoming car is below threshold.

Since a driver has first-hand phenomenal and metric knowledge of his own speed and can judge distance with reasonable accuracy, much of the variability in passing judgment apparently is associated with insensitivity to oncoming-car speed. It thus appeared reasonable to assume that if drivers were relieved of the necessity of judging oncoming-car speed, passing-judgment accuracy would improve. Results of a series of studies conducted by the present authors to evaluate this hypothesis clearly showed that providing subject drivers with verbal knowledge of oncoming-car speed significantly improved their passing judgment.

To use verbal knowledge of oncoming-car speed effectively, a driver must also consider the speed of the car he is following, since the oncoming-car—lead car closing rate determines whether or not a pass is safe at a given distance. Thus, however he uses the information, a driver given knowledge of oncoming-car speed must consider two numbers. For this reason, it was felt that the verbal knowledge of closing rate would simplify the judgment process and would improve the accuracy of the passing judgment more than verbal knowledge of oncoming-car speed. The major objective of the present study was to compare the relative utility of oncoming-car speed information and closing-rate information. A secondary purpose was to determine the ability of drivers to consider their own speed in deciding whether or not to pass.

METHOD

Ten subjects were used, all Philadelphia public-school teachers with a minimum of 8 years driving experience. The experiments were conducted on a completed but unopened section of I-95 in Philadelphia. The test section provided over a mile of sight distance, of which 3500 ft was straight and level. The tests were conducted on one side of the expressway, which contained four 12-ft lanes.

Three cars were used in the test. A Rambler sedan and an Ambassador station wagon, loaned to the project by American Motors, were used as the oncoming car and lead car; a 1965 Ford sedan, with power steering, automatic transmission, and a 356-cu in. V-8 engine, was used as the overtaking car.

At the start of each trial, the oncoming and lead cars were positioned at opposite ends of the test section; the overtaking car was positioned immediately behind the lead car (see Fig. 1). On the start signal, the oncoming and lead cars accelerated to their assigned speeds and approached each other in the two adjacent center lanes. The subject was instructed to follow the lead car closely, to estimate the time gap between his own car and the oncoming car, and to pass the lead car when the time gap closed to 12 sec. After each trial, the subject was told what the time gap actually was at the start of the pass. This technique is clearly quite sensitive to a subject's ability to judge and utilize distance, oncoming-car speed, and his own car speed. Note that, since the subject vehicle follows the lead vehicle closely before passing, passing-car speed and lead-car speed are equivalent. If subjects judged these variables perfectly, they would pass at 12 secs on every trial; therefore, ability to maintain the time gap at close to 12 sec during several trials is taken as a measure of passing-judgment accuracy.

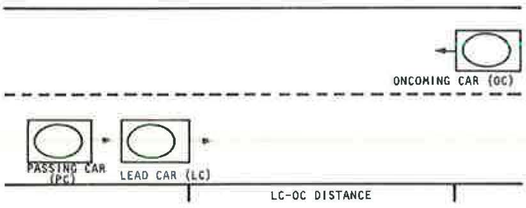

Figure 1. Experimental site.

ONCOMING CAR SPEED (MPH)	NO KNOWLEDGE				ONCOMING-CAR-SPEED KNOWLEDGE				CLOSING-RATE KNOWLEDGE			
	LEAD-CAR SPEED (MPH)											
	25	35	45	55	25	35	45	55	25	35	45	55
30												
40												
50												
60												

Figure 2. Experimental design.

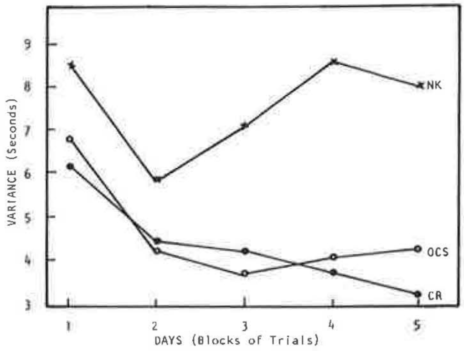

Figure 3. Variance of time-gap estimates within blocks of trials as a function of days for different knowledge conditions.

EXPERIMENTAL DESIGN

The experimental design is shown in Figure 2. Each subject performed three blocks of trials per day for 5 days. A block consisted of 16 trials, each with a different combination of lead-car and oncoming-car speeds. Lead-car speed was 30, 40, 50, or 60 mph; oncoming-car speed was 25, 35, 45, or 55 mph. Each subject had one no-knowledge (NK) block, one closing-rate knowledge (CR) block, and one oncoming-car speed knowledge (OCS) block each day. In the NK block, the subject had only his own judgment of oncoming-car speed; with CR knowledge, before each trial in a block began, the subject was told what the CR would be for that trial; and, with OCS knowledge, the subject was told before each trial in the block began what the OCS would be for that trial. The 16 speed conditions in each block were presented in a different random order each day, and the order of presentation of the knowledge-condition blocks was counterbalanced between subjects and days.

RESULTS

As shown in Figure 3, the variance of the time gap judged by the subjects to be 12 sec is less for both knowledge conditions than for the no-knowledge conditions. The difference between the two knowledge conditions are not significant; the difference between each knowledge condition and the no-knowledge condition is significant on days 3 through 5. The no-knowledge variances exhibit no systematic trend across the 5 days of practice and tend to remain high. The variances associated with knowledge conditions, however, decrease significantly with time, indicating a practice effect. The knowledge condition did not affect the average time gap at which subjects passed across all speed combinations; this gap ranged from 14.3 to 14.5 sec for the three conditions.

The effects on passing time of lead-car speed and of oncoming-car speed, with and without knowledge, are shown in Figure 4. The points on the graph show the average passing car—oncoming car time gap judged to be 12 sec for each of the three knowledge conditions and for each lead-car speed. The sloping line on each graph indicates the distance equivalent to 12 sec at each oncoming-car speed; thus, if all subjects had passed at exactly 12 sec, the line would pass through all the points.

The deviation of knowledge-condition points from the line indicates how well the subjects could use the knowledge of oncoming-car speed or closing rate. The no-knowledge subjects show no systematic response to oncoming-car speed and tend to pass a constant distance within each lead-car speed category. With either oncoming-car speed knowledge or closing-rate knowledge, the subjects passed at greater distances as oncoming-car speed increased. However, the slope of the increase is less than the slope of the 12-sec line, indicating that even under the knowledge condition subjects tended to pass slightly early at low oncoming-car speeds and slightly late at high oncoming-car speeds. Nevertheless, performance under either knowledge condition is considerably better than under the no-knowledge condition. Note that at a lead-car speed of 55 mph the average

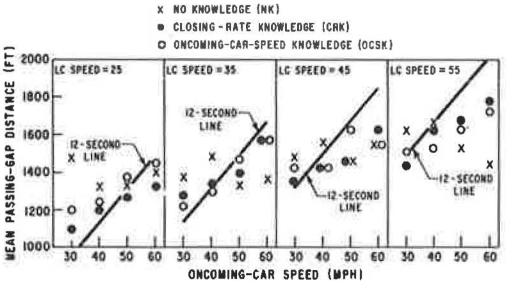

Figure 4. Mean passing distance as a function of OCS for different lead-car speeds.

no-knowledge passing distance when oncoming-car speed was 60 mph was actually less than the average passing distance when oncoming-car speed was 30 mph.

Under all conditions, as lead-car speed increased, subjects passed at greater distances. However, as lead-car speed increased, the points fall further below the 12-sec line, indicating that at high lead-car speeds subjects tended to pass slightly late, that is, to overestimate the time gap between the lead and oncoming cars.

In Figure 5, the average passing distance is plotted as a function of closing rate for each of the three knowledge conditions. Because of the oncoming and lead-car speed combinations used, all the closing rates except 55 and 115 mph appear more than once. Both knowledge conditions show an increase in passing distance with closing rate, with less of a slope than than of the 12-sec line. Because subjects, even with no knowledge, tended to respond appropriately to lead-car speed, the NK points follow a slight slope; however, the NK points are considerably more scattered than the K points.

Figure 6 shows the least-squares fit line of passing distance as a function of closing rate for the three knowledge conditions; the 12-sec line is also shown for comparison. The correlations between closing rate and distance for the NK, OCS, and CR conditions were 0.18, 0.60, and 0.62. The no-knowledge condition slope is nearly horizontal, while the slopes of the two knowledge conditions are less steep than that of the 12-sec line. Thus, subjects passed slightly early at low closing rates, and slightly late at high closing rates; that is, at low closing rates they underestimated the time gap between lead and oncoming cars, and at high closing rates they overestimated the time gap.

To estimate the time gap realistically when provided only with oncoming-car speed, subjects had to consider their own speed. When given closing-rate information, subjects should have ignored their own speeds because, under either knowledge condition at a given closing rate, passing distance equivalent to 12 sec is independent of lead-car speed. However, as shown in Figure 7a, subjects with oncoming-car speed knowledge passed at greater distances as lead-car speed increased, within each closing rate. As shown in Figure 7b, subjects with closing-rate information also tended to pass at greater distances with increasing lead-car speed, although not so markedly as did subjects with oncoming-car speed knowledge. Thus, subjects did not base their estimates of the time gap solely on closing rate and distance, regardless of the information they had been provided; however, subjects with closing-rate information apparently were less liable to misuse lead-car speed information.

Oncoming-car information is best used by summing it with the passing-car speedometer reading and basing the time-gap estimate on the resulting closing rate and on distance; however, interviews with subjects following the last experimental ses-

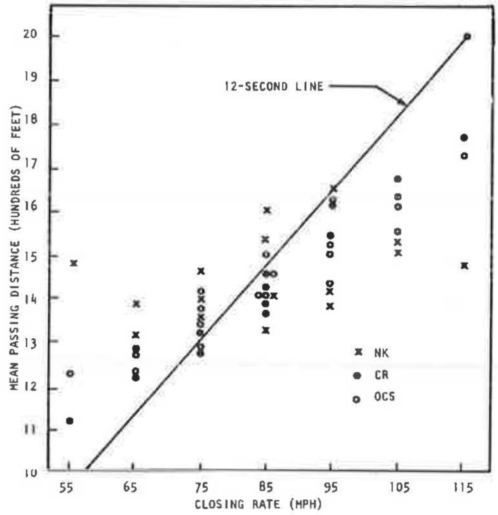

Figure 5. Mean passing distance as a function of closing rate for three knowledge conditions.

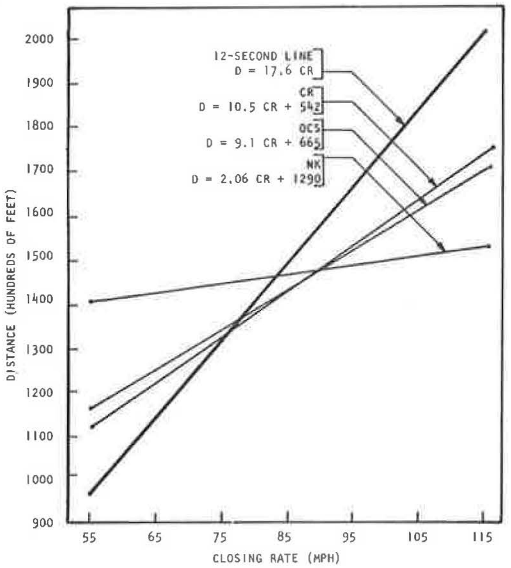

Figure 6. Least-squares fit of passing distances as a function of closing rate for three knowledge conditions.

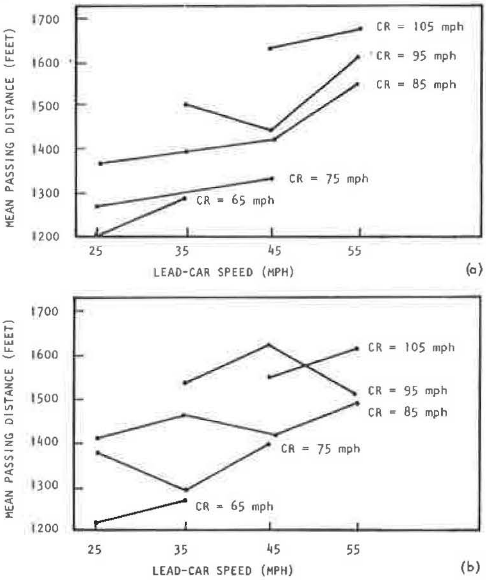

Figure 7. Passing distance as a function of lead-car speed for different closing rates with (a) oncoming-car speed knowledge and (b) closing-rate knowledge.

sion revealed that they did not use this procedure. In fact, 6 of the 10 subjects indicated that, when given closing-rate information, they subtracted their own speed from the closing rate to obtain oncoming-car speed. Thus, if subjects had been given more detailed instructions concerning how to use the information provided, they probably would have performed better.

CONCLUSIONS

On the straight roadway of the test site, subjects could not judge oncoming-car speeds. When subjects were provided with knowledge of either closing rate or of oncoming-car speed, they judged the time gap between their own car and an oncoming vehicle better than when they were not given this information; however, they used this information imperfectly and passed slightly early at low closing rates and slightly late at high closing rates. Similarly, subjects under all conditions could take their own speed into account appropriately, but tended to pass slightly early at low lead-car speeds and slightly late at high lead-car speeds. With either type of knowledge, when closing rate was constant, subjects responded inappropriately to lead-car speed by passing at greater distances as lead-car speed increased. In general, subjects used verbal information about closing rate or oncoming-car speed as well as they did that of lead-car speed about which they had phenomenal as well as speedometer information. Performance under the two knowledge conditions did not differ, either practically or statistically. Variance of the passing-time gap with either knowledge condition was about half of that resulting from the no-knowledge condition.

The application of these data is straightforward. Although the passing behavior of drivers on public highways varies considerably, the threshold passing distance adopted by drivers tends to remain constant regardless of oncoming-car speed; this distance is appropriate only for oncoming-car speeds close to or slightly above speed limits. Therefore, drivers miss passing opportunities when oncoming traffic is slow and frequently accept hazardous passing opportunities when the oncoming vehicle is traveling 10 or 15 mph above the speed limit. If drivers knew either the oncoming-car speed or the closing rate, more of them probably would pass when they should and fewer would pass when they should not.

Providing closing-rate information is technically complex; however, oncoming-car speed information appears to be equally effective and is much easier to provide. Much research currently is being performed toward developing vehicle lighting systems that convey more information than is provided on present vehicles; such a system could include information about vehicle speed. By incorporating such systems on all motor vehicles, safety and throughput on two-lane highways could be significantly improved.

ACKNOWLEDGMENT

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A Theory for Driver Steering Control of Motor Vehicles

DAVID H. WEIR and DUANE T. McRUER, Systems Technology, Inc., Hawthorne, California

The viewpoint and principles of guidance and control theory provide the basis for structuring an analytical model that describes the driver's steering control of motor vehicles. The model has as its elements the vehicle equations of motion, experimentally derived models for the human operator's dynamic response characteristics, and descriptions of the roadway environment. A variety of single-loop and multiloop feedback systems are synthesized and examined to select three good but simple and likely alternative system configurations: time-advanced lateral deviation, which has a primary outer-loop feedback of lateral position in the lane with lead equalization provided by perceptual preview along the future track of the vehicle; path angle plus inertial lateral deviation, which contains a path angle inner loop and a lateral position outer loop; and heading angle plus inertial lateral deviation, which has both heading angle and lateral position feedback loops. The resultant models give the highway engineer an analytical tool that can be used to determine the role of each system element (driver, vehicle, etc.), to define the interaction between elements, and to assess the effect of changing system parameters at the preliminary design stage.

•SOME form of steering control is required from the driver in making a vehicle perform a maneuver or follow the desired path in the presence of disturbance inputs from gusts or the roadway. To understand driver control quantitatively it is necessary to consider the actions of random and deterministic inputs on a dynamic system comprising a vehicle whose equations of motion are known and a driver whose dynamic response under various conditions can be estimated.

To accomplish the driving task with comparative safety, two things are needed:

- A desired path or maneuver (the command input) having adequate tolerances to offset variations in decision and judgmental processes, and
- A guidance and control system structure to execute the command inputs with reasonable ease and precision.

Recent research (1, 2) has centered on the guidance and control area; this has included the derivation, validation, and exercise of appropriate operational models for the driver/vehicle/roadway system.

This paper is devoted to studies of steering or directional control. These are important for many reasons, not the least being that many hazardous driving situations involve steering difficulties, and that this type of control is poorly understood for any phase of driving. Throttle and braking (longitudinal) control by the driver is also important, but it has been studied more extensively (3-9) and it is relatively well understood.

The paper begins with an overview of the sytem structure to place the component elements in an overall system context. Then the components, that is, the dynamics of the vehicle and of the driver, are summarized. With the elements defined in some detail, the structure of the driver/vehicle closed-loop system is then reexamined thoroughly,

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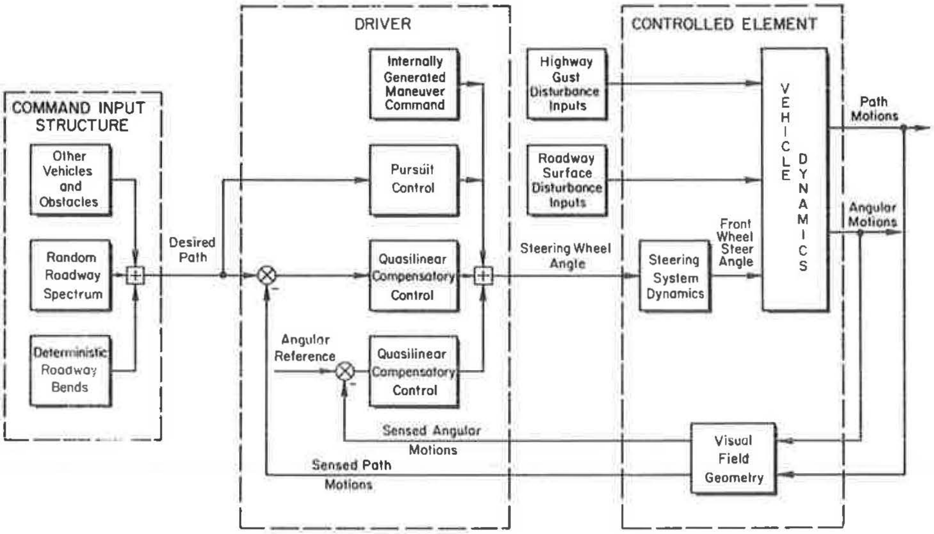


Figure 1. Topology of the closed-loop control structure.

considering both single-loop and multiloop forms. Finally, some implications of the theory are presented.

OVERVIEW OF THE MODEL STRUCTURE

The driver, the vehicle, and the roadway environment are the three essential parts of the closed-loop structure for a single vehicle element. The general topology of this structure for steering control is presented in Figure 1. It illustrates the possible types of driver response blocks, how the driver interacts with the vehicle, and how the driver/vehicle system interacts with the roadway environment.

Three general levels of control structure are shown for the driver in Figure 1. They correspond to three levels of driver behavior, and consequent system structure and performance, and are elements of the "Successive Organization of Perception" of McRuer and Krendel (10). The levels are as follows:

Precognitive, which involves executing a learned maneuver in an open-loop way. It is typified by the "Internally Generated Maneuver Command" block. The command comes from within the driver after being triggered by some pattern or stimulus in the visual and/or proprioceptive field. Examples might include turning into one's driveway, or portions of an overtaking and passing maneuver such as the initial pullout.

Pursuit, which takes advantage of a knowledge of the system input to structure a driver feedforward which improves performance (11). It is shown in Figure 1 as the "Pursuit Control" block. The essence of pursuit behavior is the combined open-loop/closed-loop characteristic. The open-loop feedforward element provides a driver output which causes the vehicle output to very nearly duplicate the command input, while the closed-loop portion of the system acts as a vernier control to reduce any residual errors.

Compensatory, which implies an operation on a perceived error between the actual vehicle motion and the desired motion or input quantity. This type of control is used in the blocks labeled "Quasilinear Compensatory Control" in Figure 1. Compensatory differs from pursuit in that the errors only are the basis for control and command inputs are not used to structure a feedforward to the driver's output.

The levels of control activity shown are very general concepts which, nonetheless, can be applied to make predictions of system behavior. Their applicability to automobile control is limited mostly by the analyst's ability to isolate the pertinent motion error cues from the visual field geometry so that an effective controlled element can be defined.

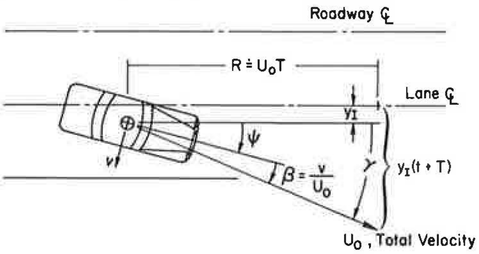


Figure 2. Motion quantities for directional control.

The controlled element contains the dynamics of the vehicle and the steering system, as well as the geometry of the visual field from which the driver must extract the guidance and control cues. Driver steering control, as well as various disturbance inputs from the environment (e. g., highway gusts and roadway roughness), act on the controlled element. The resultant controlled element motions are fed back to the driver.

The roadway environment provides inputs to the system, including both commands to be followed and disturbances to be regulated against. The command input structure includes vehicles and other obstacles on the roadway; a roadway spectrum for those that curve in a random-appearing way; and discrete or deterministic roadway bends. Portions of each of these combine to give the desired path or trajectory in a given driving situation.

All the blocks in Figure 1 contain a frequency or time function for modeling purposes. In fact, the essence of this approach is the derivation and exercise of these functions and their interaction during various driving situations, and the drawing of implications therefrom. The operational blocks (those with inputs and outputs) contain frequency functions derived from a linear or quasilinear set of differential equations. The functions in the input blocks result from such things as spectral analyses of environmental data, or time domain approximations with known deterministic forms.

Before a more specific analysis and definition of the various possible feedback loops can be made it is necessary to have a complete understanding of the dynamic characteristics of the vehicle and the driver alone. This is accomplished below, and then attention is again focused on the closed-loop structure.

VEHICLE DYNAMICS

The dynamics of the vehicle are an important part of the effective controlled element dynamics as shown in Figure 1. The driver/vehicle/roadway model examined here considers the directional or steering dynamics of the passing vehicle in three degrees of freedom. These degrees of freedom are lateral (or side) velocity, v, and heading angle, ψ, of the total vehicle; and the sprung mass (body) roll angle, φ, as shown in Figure 2. Effects on the directional characteristics due to acceleration or braking in the longitudinal axes are included implicitly; i. e., the stability derivatives in the directional equations are computed for some known applied torque at the front and rear wheels. Road crown, grade, and superelevation are handled in a similar way by computing the vehicle equations for a nominal set of conditions or an operating point. This approach allows the use of linearized equations and analyses that allow greater insight into the control problems, yet provide good accuracy for vehicle side accelerations less than about 0. 3 g (12).

The Laplace-transformed directional equations in three degrees of freedom are given by the following matrix equation (1):

$$\begin{bmatrix} s - (Y_v + Y_{v_g}) & \frac{m_s e}{m} s^2 - Y_\varphi & U_o - Y_r \\ \frac{m_s e}{I_\varphi} s - L_{v_g} & s^2 - L_p s - L_\varphi & \frac{I_{\varphi z}}{I_\varphi} s - L_r \\ -(N_v + N_{v_g}) & \frac{I_{\varphi z}}{I_{zz}} s^2 - N_p s - N_\varphi & s - N_r \end{bmatrix} \begin{bmatrix} v \\ \varphi \\ r \end{bmatrix} = \begin{bmatrix} Y_{\delta_w} \\ 0 \\ N_{\delta_w} \end{bmatrix} \delta_w + \begin{bmatrix} -Y_{v_g} \\ -L_{v_g} \\ -N_{v_g} \end{bmatrix} v_g \qquad (1)$$

where

v	is the lateral velocity of the unsprung mass measured at the total vehicle c. g.,
φ	is the roll angle of the sprung mass about the tilted roll axis,
r	is the yaw (heading) rate of the unsprung mass,
s	is the Laplace transform variable,
Y_v, Y_r, Y_{δ_w}	are a result of tire side force,
Y_{v_g}	is a result of aerodynamic force,
Y_φ	is a combination of roll steer and camber effects,
L_{v_g}	is a result of aerodynamic force,
L_φ	is a combination of gravity and suspension spring effects,
L_p	is due to the shock absorbers and suspension friction,
L_r	is equal to $-m_s e U_0/I_\varphi$,
N_v, N_r, N_{δ_w}	are a result of tire side force,
N_{v_g}	is a result of aerodynamic force,
N_φ	is a combination of roll steer (leading to tire side force), camber side force, and suspension spring effects,
N_p	is due to shock absorbers and suspension friction,
m	is the total mass,
m_s	is the sprung mass,
I_φ	is the roll moment of inertia,
I_{zz}	is the yaw moment of inertia,
$I_{\varphi z}$	is the product of inertia coupling roll and yaw,
e	is the perpendicular distance from the roll axis to the sprung mass c.g.,
U_0	is the forward velocity,
δ_w	is the mean front wheel steer angle about the kingpin, and
v_g	is a lateral velocity gust input.

The motion quantities are shown in Figure 2. This matrix equation of motion provides vehicle motion quantities as perturbations of body-fixed axes. To obtain the vehicle motions in inertial space (e. g., along a roadway) it is necessary to transform the body axis motion quantities into appropriate inertial reference axes. The lateral velocity relative to an inertial coordinate system initially coincident with the unperturbed body axes is given by the integral of the lateral acceleration of the c. g., that is,

$$\begin{aligned} v_I(t) &= \int a_y(t)\, dt \\ &= \int [\dot{v}(t) + U_0 r(t)]\, dt \\ &= v(t) + U_0 \psi(t) \end{aligned} \tag{2}$$

In Laplace transform notation this becomes

$$v_I(s) = v(s) + U_0 \frac{r(s)}{s}$$

Dividing the inertial lateral velocity by U_0 gives the path angle, γ, which is the sum of the heading angle and sideslip, that is,

$$\gamma = \frac{v_I}{U_0} = \beta + \psi \tag{3}$$

The lateral position relative to inertial coordinates is the integral of the inertial lateral velocity, that is,

$$y_I(s) = \frac{sv(s) + U_0 r(s)}{s^2} \tag{4}$$

This gives the lateral position between the car and a roadway reference at the vehicle c. g.

A motion useful in the subsequent closed-loop analyses is the lateral position the vehicle will have T seconds in the future if it continues unperturbed along its present trajectory. This is denoted by $y_I(t + T)$ and is shown in Figure 2. The time, T, is equal to the distance, R, to the future point divided by the vehicle speed, U_0.

Lateral acceleration at the driver's position in the vehicle, a_y, is the sum of the inertial acceleration at the axis system origin, $\dot{v}_I$, plus the effect of yawing and rolling accelerations acting through distances to the driver's position, that is,

$$a_y = \dot{v}_I + l_x\dot{r} + (l_x \sin \lambda - l_z \cos \lambda)\dot{p} \tag{5}$$

where

l_x is the distance in the positive x direction from the total vehicle c. g. to the driver,
l_z is the distance in the positive z direction from the axis system origin to the driver,
λ is the sprung mass roll axis tilt angle.

Laplace-transforming Eq. 5 and introducing $v_I(s)$ gives

$$a_y = sv(s) + (l_x \sin \lambda - l_z \cos \lambda)sp(s) + (l_x s + U_o)r(s) \tag{6}$$

It is common practice in stability and control analyses to solve the matrix equation (Eq. 1) to obtain ratios of motion variables to selected input quantities. The resultant ratios of polynomials in s are called transfer functions. Three types of polynomials are obtained—the denominator, which is always the determinant of the left-hand side of Eq. 1; numerators, which are the determinants obtained by substituting one of the right-hand column vectors into the determinant of the left-hand side; and coupling numerators, which are the determinants obtained by substituting the two right-hand column vectors into the determinant of the left-hand side in various ways. The coupling numerators are used in multiloop analyses (e. g., gust regulation) to obtain the effect on outer-loop numerators of inner-loop closures utilizing another control means. Their use is discussed in detail elsewhere (13, 2).

A complete summary of the vehicle dynamics pertinent to driver control is given by Weir et al (1). It includes the derivation of the equations of motion, definition of the vehicle transfer functions, compilation of dynamic data from a number of sources, and the calculation of numerical results for a typical American sedan. Both longitudinal and directional dynamics are included, with the emphasis on the latter. Most of the details of the vehicle dynamics are omitted here, the needed information having been extracted from the previous work (1) when required.

Vehicle transfer functions have been computed (1) for a typical medium-sized American sedan weighing about 4000 lb at speeds of 30, 60, and 75 mph. The transfer functions are represented symbolically as follows:

Lateral velocity:

$$\frac{v}{\delta_w}(s) = \frac{N^{v}_{\delta_w}(s)}{\Delta(s)} \tag{7}$$

Heading angle:

$$\frac{\psi}{\delta_w}(s) = \frac{1}{s}\,\frac{r}{\delta_w}(s) = \frac{N^{r}_{\delta_w}(s)}{s\Delta(s)} \tag{8}$$

Roll angle:

$$\frac{\varphi}{\delta_w}(s) = \frac{N^{\varphi}_{\delta_w}(s)}{\Delta(s)} \tag{9}$$

TABLE 1

TRANSFER FUNCTIONS FOR TYPICAL AMERICAN SEDIAN[a]

POLYNOMIAL	30 MPH	60 MPH	75 MPH
Lateral velocity numerator, $N^{v}_{\delta_W}(s)$	$180(s+.188)[s^2+2(.305)(6.38)s+(6.38)^2]$	$180(s-9.50)[s^2+2(.284)(6.94)s+(6.94)^2]$	$180(s-13.1)[s^2+2(.275)(7.00)s+(7.00)^2]$
Yaw rate numerator, $N^{r}_{\delta_W}(s)$	$24.3(s+9.49)[s^2+2(.278)(6.66)s+(6.66)^2]$	$24.3(s+4.35)[s^2+2(.284)(6.95)s+(6.95)^2]$	$24.3(s+3.40)[s^2+2(.279)(7.03)s+(7.03)^2]$
Roll angle numerator, $N^{\phi}_{\delta_W}(s)$	$-49.04[s^2+2(.570)(6.85)s+(6.85)^2]$	$-49.04[s^2+2(.284)(6.85)s+(6.85)^2]$	$-49.04[s^2+2(.228)(6.85)s+(6.85)^2]$
Lateral acceleration at origin numerator, $N^{a_{y_o}}_{\delta_W}$	$180[s^2+2(.194)(6.73)s+(6.73)^2][s^2+2(.499)(7.43)s+(7.43)^2]$	$180[s^2+2(.293)(6.91)s+(6.91)^2][s^2+2(.160)(7.24)s+(7.24)^2]$	$180[s^2+2(.279)(6.77)s+(6.77)^2][s^2+2(.125)(7.39)s+(7.39)^2]$
Characteristic denominator, $\Delta(s)$	$.684[s^2+2(.296)(7.03)s+(7.09)^2][s^2+2(.986)(9.17)s+(9.17)^2]$	$.684[s^2+2(.785)(5.84)s+(5.84)^2][s^2+2(.290)(6.97)s+(6.97)^2]$	$.684[s^2+2(.670)(5.306)s+(5.31)^2][s^2+2(.309)(6.92)s+(6.92)^2]$

[a] As given in Weir et al (1).

where N(s) is a numerator polynomial in s and $\Delta(s)$ is a denominator polynomial in s. The numerator and denominator polynomials for the three forward speeds are given in Table 1. A fairly significant difference can be seen in the dynamics between 30 and 60 mph, while there is little difference between the results at 60 and 75 mph. This indicates that one set of directional dynamics (i. e., one operating point) can be used to analyze typical high-speed driving maneuvers which involve speed changes of no more than about 15 to 20 mph.

Analysis has shown that the aerodynamic forces and moments have only a negligible effect on the steer angle transfer functions of Table 1. [They are, of course, dominant in the gust response transfer functions, through which a highway gust disturbance input acts on the vehicle—see Weir and McRuer (2), where the equations and transfer functions required to introduce crosswind gusts into the driver/vehicle system are derived and summarized.]

The series dynamics of the steering system are an important part of the vehicle dynamics and the effective controlled element. They relate the driver's steering wheel movement to the steer angle of the front wheel about the kingpin. Although the theory is well understood (e. g., 14), dynamic data on contemporary steering mechanisms is very sparse. Consequently, the steering system dynamics are assumed to be a pure gain for purposes of this discussion. The effects of possible steering lags on closed-loop control are considered elsewhere (2).

DRIVER DYNAMIC RESPONSE

All phases of driving require some form of driver control operation. As the tasks become more demanding, the driver may change his dynamic characteristics or may alter the system structure (close other loops) to obtain the required increase in control fidelity. The driver's closure of feedback loops modifies the effective dynamics of the vehicle or controlled element and in turn determines maneuver times, stability margins, and transient response characteristics. The possible feedback loops he can introduce are determined by the sensory information available.

An introductory discussion of driver response characteristics was illustrated in Figure 1, and several possible types of driver response were presented:

- Quasilinear compensatory control,
- Pursuit control, and
- Internally generated maneuver commands.

The first requires a fairly complex description, but it is well understood at the current time and probably comprises a significant portion of the driver's active control efforts. The remaining two are somewhat easier to describe qualitatively, but predictive models for these processes are not yet well developed.

The quasilinear blocks in the driver/vehicle model are most appropriate for defining his response to random-appearing external inputs. This includes command inputs due to the bends and curves in the roadway or desired path, as well as disturbance inputs due to gusts and roadway roughness. These quasilinear blocks are relatively quiescent in the presence of deterministic inputs when the other types of response dominate. They are active during pursuit control if random-appearing disturbances are also present that the driver cannot preview.

Quasilinear Compensatory Control Characteristics

The quasilinear describing function model of the operator has resulted from an exhaustive series of human operator dynamic response measurements made over a period of about two decades (e. g., 15-18). It consists of a describing function component with parameters that depend on the system and situation, an additive remnant, and a set of adjustment rules that tell how to adjust the describing function parameters. This quasilinear model is depicted in the illustrative single-loop block diagram of Figure 3.

In its most complete form the describing function contains a gain, an indifference threshold, a time delay, an equalization characteristic, and high-frequency neuromuscular system dynamics. The indifference threshold is a higher order effect that can

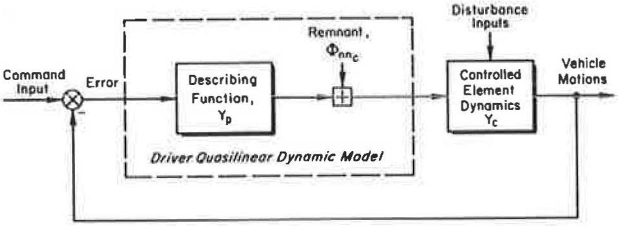


Figure 3. Driver model for quasilinear compensatory control.

often be ignored when the inputs are large, and under other conditions it can be accounted for by using decreased driver gain. The neuromuscular system dynamics are based on very low and very high frequency data, and can be approximated at the midfrequencies of interest in driving as a first-order lag or even as an added increment to the time delay. With these simplifications, the general driver describing function (2) reduces to

$$Y_p \doteq \frac{K_p e^{-j\omega\tau}(T_L j\omega + 1)}{(T_I j\omega + 1)(T_N j\omega + 1)} \tag{10}$$

or, alternatively,

$$Y_p \doteq K_p \left(\frac{T_L j\omega + 1}{T_I j\omega + 1}\right) e^{-j\omega(\tau + T_N)} \tag{11}$$

where

K_p is the gain,

$\left(\frac{T_L j\omega + 1}{T_I j\omega + 1}\right)$ is a simplified equalization characteristic,

τ is the time delay, and

T_N is the neuromuscular system time constant.

The variable $j\omega$ has been used in place of s to indicate that the describing function is most appropriate when the inputs approximate stationary random processes. The form of Eq. 11 is completely adequate for typical driver/vehicle closed-loop analyses involving reasonably stable vehicles. Thus, the describing function form reduces to a transfer-function-like element containing a gain, an adjustable equalization, and an exponential term which affects only the phase angle. It is valid for a variety of drivers, inputs, vehicle dynamics, steering system characteristics, and loop structures. Most of the parameters are adjustable as needed to make the vehicle motions follow the command input and regulate against the disturbance input. Experimental measurements of all the parameters are reported elsewhere (2) and summarized in a simplified manner below.

The pure time delay represented by the $e^{-j\omega\tau}$ term is due to sensor excitation (the retina, in the visual case), nerve conduction, computational lags, and other data-processing activities in the central nervous system. It contains components that are closely related to certain kinds of classical reaction times. A portion of the time delay is currently taken to be a constant, because it appears to be essentially invariant with the input and vehicle dynamics for either single or dual random-appearing input tasks. However, both intersubject and intrasubject variations occur, and observed values of the "constant" part of τ range from about 0.05 to 0.125 sec, with a nominal value of about 0.10 sec (15). The remaining component of the pure time delay is an increment present when low frequency lead equalization is generated by the driver. For instance, with first-order lead equalization the base value of τ is increased by about 0.15 sec.

The neuromuscular time constant, T_N, is partially adjustable for the task. The nature of the adjustment is input-adaptive, consisting of a monotonic decrease in T_N

with increasing forcing function bandwidth, ω_i. The data (15) show that the incremental reduction is approximately

$$\Delta T_N = 0.08\omega_i \ , \quad \omega_i \le 4 \text{ rad/sec} \tag{12}$$

The observed variation of T_N with forcing function bandwidth ranges from less than 0.1 sec to almost 0.5 sec. In cases where the input bandwidth is not known, typical values of T_N near 0.1 sec are sometimes used.

The equalizing characteristics, $(T_L j\omega + 1)/(T_I j\omega + 1)$, coupled with the gain, K_p, are the major adaptive elements of the human that allow him to control many differing dynamic devices. Their function is the modification of the stimulus signal into a suitable neuromuscular command that is properly scaled and phased for proper overall man/machine system operation. For given input and vehicle dynamic characteristics, the form of the equalizer is adapted to compensate for the vehicle dynamics and the driver's pure time delays. The major cost of equalization is the increase in time delay incurred when low-frequency lead is needed as part of the compensation.

The major "adjustment rules" for the equalization characteristics, evolved as generalizations of many experiments, are that a particular equalization is selected from the general form $K_p(T_L j\omega + 1)/(T_I j\omega + 1)$ such that the following properties are attained:

- The driver/vehicle system can be stabilized by proper selection of gain, preferably over a very broad region.
- The amplitude ratio of the product of the driver describing function and the vehicle dynamics, $|Y_p Y_c|$, has approximately a -20 dB/decade slope in the crossover region—that frequency band centered on the crossover frequency, ω_c.
- $|Y_p Y_c| \gg 1$ at low frequencies to provide good low-frequency closed-loop response to system commands and good suppression of the effects of disturbances.

Simplified Crossover Model for the Driver Describing Function—The preceding remarks about the rationale of equalization adopted by the driver can be simplified by using an approximate "crossover model." The experimental data and consideration of the requirements of good feedback system performance both lead directly to the conclusion that the driver adjusts his describing function so that the open-loop function, $Y_p Y_c$, in the vicinity of the gain crossover frequency, ω_c, has the approximately invariant form

$$Y_p Y_c \doteq \frac{\omega_c e^{-j\omega \tau_e}}{j\omega} \tag{13}$$

where τ_e is an effective pure time delay that includes the neuromuscular time constant, T_N, as well as τ and any net high-frequency controlled element lag. The gain term is the crossover frequency.

The bandwidth and performance of the driver/vehicle system are proportional to ω_c, while errors and response time vary inversely with it. The driver adopts either proportional control, or lead or lag equalization, such that the product of the equalization and the vehicle has the form shown, with which it operates on the perceived motion error. The numbers (ω_c and τ_e) in the crossover model depend on the driver equalization. Specifically, the crossover frequency is greatest and the effective time delay is least when the driver's equalization is a low-frequency lag. Alternatively, ω_c is least and τ_e the greatest for low-frequency lead. Thus the closed-loop bandwidth will be reduced for low-frequency lead and greatest when only lag is needed. Since most characteristics of the driver/vehicle system (such as response time) are dependent on bandwidth, the performance with low-frequency lead is inferior to that with lag.

Experimental values of crossover frequency, ω_c, and phase margin, φ_M, for several dynamic forms and input bandwidths are given in Table 2. The controlled element, Y_c, forms shown are limiting versions. They can be considered as approximations in the

TABLE 2

OPERATOR PHASE MARGINS AND CROSSOVER FREQUENCIES[a]

Y_c	ω_i = 1.5 rad/sec		ω_i = 2.5 rad/sec		ω_i = 4.0 rad/sec	
	φ_M (rad)	ω_c (rad/sec)	φ_M (rad)	ω_c (rad/sec)	φ_M (rad)	ω_c (rad/sec)
K_c	0.51	5.1	0.75	5.7	0.75	6.7
K_c/s	0.42	4.6	0.73	4.7	0.94	5.0
$K_c/(s-2)$	0.35	4.6	0.66	5.0	0.70	5.2
K_c/s^2	0.26	3.2	0.51	3.3	0.73	1.8

[a] As abstracted from McRuer et al (15).

region of crossover to the more complex dynamic descriptions resulting from the vehicle equations of motion.

The crossover frequencies in Table 2 are maximum values for skilled subjects in fixed-base simulators without motion feedbacks. These will ordinarily be considerably reduced during driving, especially when full attention is not demanded. The maximum extent of this reduction can be readily estimated for conditionally stable systems on the basis of stability alone. To obtain an estimate of the full-attention driving value for vehicles that are always stable, consideration should be given to

- Gain reduction,
- τ_e increase, due to conflicting demands,
- τ_e increase, due to steering dynamics, especially when holding trim loads against road crown or steady crosswinds, and
- Statistical variation in ω_c with time and between subjects.

This leads, in practice, to larger phase and gain margin criteria, typical examples of which are used in the driver/vehicle loop closures shown below and elsewhere (2).

In many driving situations the driver's regulation or control activity is only intermittent, so the average crossover frequencies will invariably be less than those estimated for full-attention driving. This reduction is probably due primarily to an increase in indifference threshold, and thus may not result in much of a reduction for large amplitude motions. A matter of some importance is the spread between the highest and lowest ω_c values possible (the lowest often merges with the unattended condition), which is a measure of the degree of vehicle configuration forgiveness. This or an associated measure also implies limitations on indifference threshold, sampling, minimum and maximum average movements per second, minimum and maximum information rates, etc.

Driver Remnant Characteristics—The remnant is that portion of the driver's output not linearly correlated with the input. It is always present to some extent, and it is probably the most significant undesired input into the steering system from a practical standpoint. The remnant is considered to be a random process that is added to the output of the driver's describing function block to form the total driver's output. It is denoted by a power spectral density, Φ_{nn}, in Figure 3. The point of application could be moved to other places in the loop as long as no nonlinear elements are passed in the process. The remnant can have significant power at frequencies that are high enough to excite lightly damped high-frequency steering system modes present under conditions of low Coulomb friction (e.g., 14).

The major source of remnant appears to be nonstationarity in the operator's behavior (15), manifest as time-varying components in the gain, K_p, and the effective time delay, τ_e. The remnant component due to τ_e variation is usually increased when low-frequency lead is generated by the driver. Also, low-frequency lead is associated with a pulsing behavior by the operator in which his output tends to be pulses with areas roughly proportional to the stimulus amplitude. This is an additional remnant source for controlled element dynamics requiring low-frequency lead equalization. An extensive body of remnant data shows that the remnant power increases with the order of the controlled element dynamics and with increases or decreases in controlled element gain away from an "optimum" value. It decreases with input bandwidth.

For nominally good dynamics (e.g., $Y_c \doteq K_c/s$) the remnant power is about 30 dB down relative to the input. Consequently, the remnant can usually be neglected from the standpoint of predicting driver/vehicle closed-loop response characteristics when the vehicle characteristics are reasonably good. This assumption is made in conventional analyses as a starting point. Then, if there is reason to believe that significant remnant power is present in the vehicle output motion quantities, the remnant can be added to the output of the driver/vehicle system.

Driver Response in Multiple-Loop Situations—The closed-loop structure of Figure 1 involving angle and path feedbacks is called multiloop single-point control. Multiloop implies two or more dynamically coupled motion variables and single-point refers to one control means, the steering wheel. Experimental measurements of operator response in such a multiloop situation (18) showed that the describing function in the outer loop can be obtained by application of the single-loop model described above. Thus, the equalization in an outer loop involving lateral position is obtained by direct application of the describing function model once the appropriate inner loop has been closed.

Ordinarily the inner feedback loops supplied by the driver act as parallel equalization for the outer loop, or provide feedbacks or crossfeeds which suppress subsidiary controlled element degrees of freedom that have undesirable effects on subsequent loops. Because the role of the inner loops is so dependent on outer-loop requirements, the rules cited above for the single-loop model are not generally applicable; for example, even stability of an inner loop may not be required. The types of inner loops closed and the equalization selected should be compatible with one or all of the following considerations:

- Outer-loop adjustments per the single-loop adjustment rules become more feasible; e.g., $|Y_pY_c|$ for the outer loop can be made approximately -20 dB/decade with less outer-loop equalization by the driver.
- The sensitivity of the closed-loop characteristics to changes in either inner- or outer-loop driver characteristics is reduced from that in an outer-loop-only situation. This includes the improvement of stability margins.
- The loop structure and equalization selected are those for which total subjective opinion rating is the best obtainable.

It frequently happens that the driver describing function synthesized for the inner loop alone via the single-loop model is also the one that best enhances the outer-loop closures. This is most common in situations where the basic vehicle possesses good stable dynamic characteristics, and the control task is merely following command inputs or suppressing disturbances—not stabilizing the vehicle.

Pursuit Control Characteristics

The pursuit control block in Figure 1 operates on the input using the driver's preview of a desired path, rather than a perceived motion or path error as in the compensatory case. Recent experiments (11) have shown that the describing function magnitude of the driver's pursuit feedforward block, Y_{p_i}, is approximately equal to the inverse of the magnitude of the effective controlled element dynamics, i.e., $|Y_{p_i}| = |1/Y_c|$. The net effect is to make the amplitude of the total closed-loop describing function from the command path to actual vehicle path be approximately unity (although the data show some variations in phase angle), and the commanded path and the actual path are approximately equal. The driver must be able to see and use the input itself to structure this block. The compensatory loops can be active when the pursuit loop is operative, providing, for example, vernier corrections and regulation against disturbance inputs that are most evident in the error.

Internally Generated Maneuvers

When a discrete disturbance (e.g., an isolated gust) is encountered, the change in the vehicle motion quantities is perceived by the driver as a motion error. The well-trained driver will recognize that the disturbance has a deterministic form for which there is some appropriate skilled response. If the input is a step, for example, he may make a classic response (e.g., 19) involving a time delay, a relatively rapid steering-wheel motion during a rise time phase, and an error-correcting phase. Recent operator response modeling activities (20) have concentrated on deriving and refining models for discrete inputs (such as steps and ramps) with various effective controlled element dynamics. Some potentially useful results have been obtained, but their application to the prediction of driver behavior is not yet state-of-the-art. Any discrete response block is assumed to be quiescent in the presence of low-frequency random motions, and to respond only to simple deterministic signals. During such a response the other driver blocks are assumed to be relatively inactive.

A number of the control actions made by a practiced driver during various phases of driving are done in a precognitive (or open-loop) manner. A good example is pulling out to pass and pulling back in. In this case the driver produces the appropriate steering action based on an internally generated pattern previously evolved during a learning process. He is cognizant of the effective controlled element, the command input, and the state of the motion quantities reflected in the error, but he is not operating on any motion quantity in a linear or quasilinear way. Safety aside, he could, in effect, close his eyes and complete the maneuver, leaving some residual position error at the end. The patterns produced may result in nearly optimal response according to some (as yet undefined) criterion such as minimum time or minimum overshoot. The essence of this block for maneuver command generation is that it produces whatever control signal is required to accomplish the desired maneuver to some degree of accuracy acceptable to the driver.

STRUCTURES OF DRIVER/VEHICLE CLOSED-LOOP SYSTEMS

Perhaps the most difficult problem in driver/vehicle closed-loop analysis is to determine what sensory feedback loops the driver is using. There are two general approaches to deriving the closed-loop structure: from consideration of perception and from guidance and control theory. The perceptual basis relies on in situ experimental observation of subjects driving, and can require extensive instrumentation, eye-movement cameras, highly structured and constrained experimental environments, etc. The primary aim is to discover experimentally what "cues" are used to drive. The control theory approach is to consider the driver/vehicle system as a guidance and control problem, and then to develop the kinds of vehicle motions that must be sensed and commands that must be inserted to satisfy the guidance and control needs. The guidance and control problem does not have a unique solution, so the initial results of this kind of study are a number of "sufficient systems." Consideration must then be given to the driver's ability to perceive (sense) the vehicle motion and input quantities, and to the nature of the operations required on the sensed quantities in closing the driver/vehicle system loops. Those potential systems that involve readily sensed quantities and relatively simple (e.g., proportional, minimum conscious effort, etc.) operations on the sensed motion variables are then accepted as good candidates. The control theory approach is relatively straightforward, given the current state of knowledge of typical operator/vehicle control laws and closed-loop analysis techniques. The best approach is to marry the guidance and control and the perceptual theories, for the net results must of necessity be compatible, and the two viewpoints offer much to one another as collaborators and corroborators. However, it has been necessary to rely on the control theory approach as the main tool here because of the limited amount of perceptual data relevant to vehicular control.

Single-Loop Structure

The problem of how the driver perceives the feedback variable is secondary in the deductive guidance and control approach. The objective is to determine how well the variable permits the driver to control the vehicle if it can be sensed. This is pursued by attempting to discover likely feedback loops that may exhibit good characteristics as either a command loop or as a subsidiary loop providing equalization for a command loop. It is also desired to identify those loops possessing poor characteristics as single-loop systems that either rule them out as possible feedbacks or indicate the need for inner-loop equalization, or exhibit properties that make them candidates as accident causes if they are inadvertently opened or closed.

A systematic search for likely feedback loops has been accomplished (21) using the 60 mph dynamics in Table 1 of a typical sedan (circa 1965) and the driver describing function characteristics. The search took the form of a survey of single-loop closures directed toward determining those loops that the driver might close. The quality of the resultant closures was judged by

- The equalization required by the driver to provide a stable system consonant with the "adjustment rules," and
- The closed-loop performance attainable as measured by estimated crossover frequency, stability margins, etc.

Compensatory closures were used. This is consistent with such concepts as "preview" when one considers that the effective controlled element dynamics, Y_c, include the geometry and kinematics of the external visual field as well as the dynamics of the vehicle. In essence, a guidance or control cue is perceived someplace in the visual field by the driver, and to the extent that the driver steers the vehicle to modify (e.g., follow or reduce) this cue in some way he is acting in a compensatory manner.

The results of driver/vehicle single-loop surveys are summarized in Table 3. The same closure criterion was used (where possible) for each of the loops in Table 3 in order to facilitate comparison. The same effective time delay was used in the K and K/s controlled element cases. A slightly larger time delay was used with K/s^2. In each case the time delay was larger than that given in Table 2 to account for some steering system lag. The phase margins were larger than those given in Table 2, corresponding to an attentive but "smooth" driver in the presence of a relatively high frequency input. Lower phase margin values are better for prediction, but the actual levels are not too important in a comparative analysis of the sort summarized in Table 3. The levels will vary from one driver to another in practice, depending on skill, attention, fatigue, etc., but they should all change in roughly the same way for a given driver.

Closure of an inertial lateral deviation loop is very likely necessary in order to stay in the lane or to follow a desired trajectory. The driver is assumed to be steering according to his lateral deviation with respect to an inertial axis reference such as the roadway or lane center line. Although the driver can easily perceive this motion

TABLE 3

SUMMARY OF SINGLE-LOOP SURVEYS

FEEDBACK	APPROXIMATE VEHICLE TRANSFER FUNCTION	DRIVER EQUALIZATION	ESTIMATED SYSTEM CROSSOVER FREQUENCY (rad/sec)	ESTIMATED RELATIVE DRIVER OPINION
Inertial lateral deviation $y_I \rightarrow \delta_w$	$\frac{405}{s^2}$	Large lead	1	Poor, because of large amount of lead equalization and low bandwidth
Heading angle $\psi \rightarrow \delta_w$	$\frac{4.6}{s}$	Gain only	1.5	Good
Path angle $\gamma \rightarrow \delta_w$	$\frac{405}{s}$	Gain only	1	Good, particularly with small lead equalization
Lateral velocity $v \rightarrow \delta_w$	-74	Lag/lead	.1	Fair, because of low bandwidth and lag equalization
Heading rate $r \rightarrow \delta_w$	4.6	Lag/lead	1.6	Good
Lateral acceleration at driver's head $a_y \rightarrow \delta_w$	400	Lag/lead	1	Fair, because of low bandwidth, lag equalization, and high sensitivity

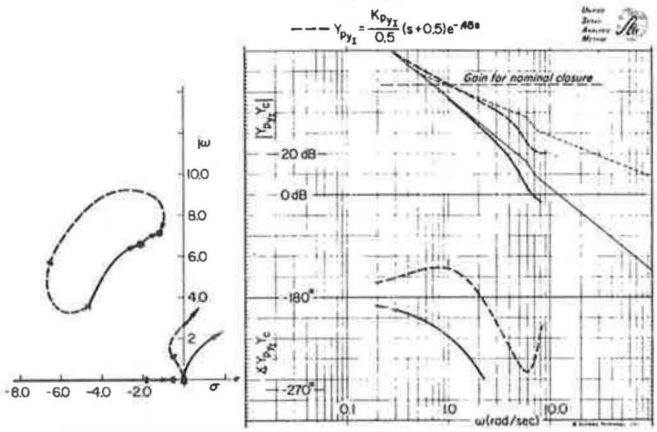


Figure 4. Inertial lateral deviation loop closure.

quantity, this single-loop control mode is relatively difficult. The effective controlled element is given by double integration of the lateral acceleration in Table 1, that is,

$$\frac{y_I}{\delta_w} = \frac{1}{s^2} \frac{N^{a_{yo}(s)}_{\delta_w}}{\Delta(s)} \qquad (14)$$

The system survey plot for driver-plus-vehicle is shown in Figure 4. The closed-loop system is unstable with a pure-gain-plus-time-delay (unequalized) driver describing function, as shown by the solid lines, because of the two poles at the origin (see root locus). A relatively large amount of driver lead equalization is required to attain even minimal stability margins. A skilled driver could add low-frequency lead at about 0.5 rad/sec and obtain a crossover frequency of about 1.0 rad/sec with 25 deg of phase margin. This is shown by the dashed lines in Figure 4, and corresponds to a driver describing function of the form

$$Y_{p_{y_I}} \doteq \frac{K_{p_{y_I}}}{0.5}(s + 0.5)e^{-0.45s} \qquad (15)$$

Although a skilled driver could achieve the lead equalization of Eq. 15 for a short period of time, it would be difficult, and he would have a poor subjective opinion of the vehicle's dynamics (22). Thus, an inertial lateral deviation loop has poor characteristics as a single-loop system, and plainly requires additional (inner) loop closures to alleviate the need for large driver lead to obtain a satisfactory driver/vehicle system bandwidth.

Although $y_I \rightarrow \delta_w$ is not a likely primary control loop because of the low bandwidth and high driver skill required, it may be important after perceptual transitions. This could occur when the driver suddenly loses his view down the road and is forced to steer on the basis of his lateral position in the lane (e.g., entering a tunnel or fog bank). Such a regression would cause him to slow down so that the lower driver/vehicle system bandwidth would still enable him to follow any likely command input.

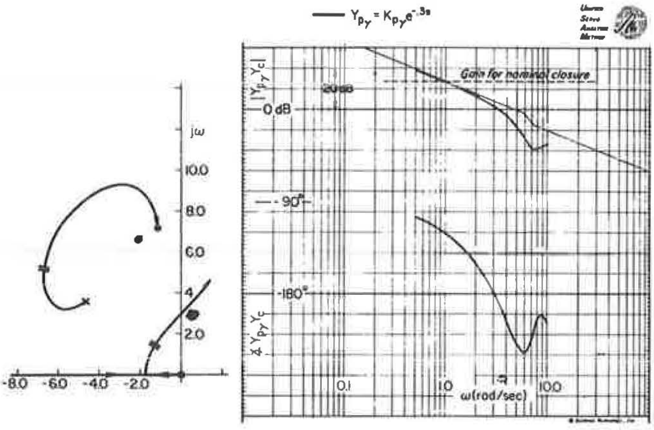


Figure 5. Path angle loop closure.

Both heading angle and path angle are control feedbacks offering good closed-loop characteristics. (Detailed surveys are shown in Figs. 5 and 6.) Path angle control combines heading control (a good loop by itself) with body axis

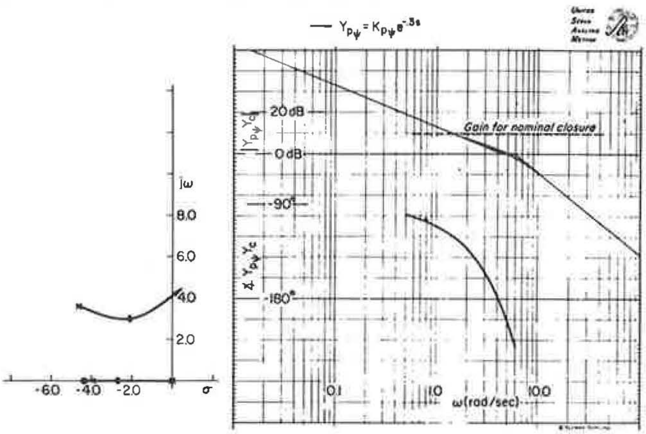


Figure 6. Heading angle loop closure.

lateral velocity (sideslip), which is only fair taken alone. Both heading angle and path angle systems can serve as outer loops if an intermittent trim loop is employed occasionally to reduce or reset the lateral deviations. Also (as described later), either of these angle systems can serve as an inner loop to reduce the lead requirements for an inertial lateral deviation outer-loop system.

The heading rate system is also good and is a conceivably useful inner loop. Path angle rate or curvature (not shown) has similar potential. It is the apparent curvature of the roadway ahead of the vehicle and has effective controlled element dynamics that are a pure gain in the region of crossover, implying driver lag equalization. The lateral acceleration at the driver's head is not a particularly good system because it is highly sensitive to driver gain variations; that is, the difference between the minimum gain required to provide some control and the maximum gain permissible without instability is not large. This also places an additional requirement on the need for relatively high driver skill.

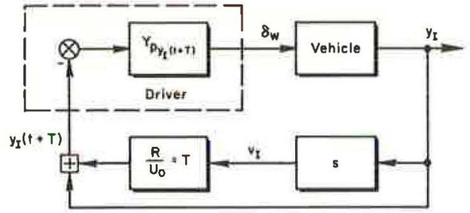
The single-loop closures in Table 3 having poor characteristics are unlikely loop closures under favorable conditions because of the poor system performance or excessive driver demands. They can, however, be important in situations where a better loop structure has been destroyed due to changes in the cues available or other disturbing factors. Under such perceptual transitions, these poor single-loop systems may momentarily prevail as a transitional phase.

Multiloop Structures

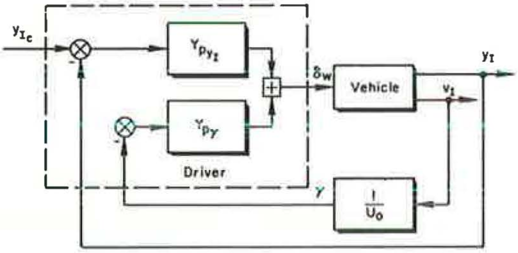
The good single-loop closures shown in Table 3 will all provide systems with good performance in following a command input of that motion variable. None of the single-loop closure systems shown will do a very good job of following a path or trajectory command input that involves minimizing lateral position (deviation) errors to stay in the center of the lane or roadway. Thus, there is a need for the driver to augment his outer-loop structure with inner loops that serve as appropriate equalization. Among these multiloop systems, those that require little or no driver equalization (i. e., only gain plus time delay in each of the loops) are to be preferred from both a closed-loop performance and a driver subjective opinion standpoint.

Three different multiloop systems have evolved to date. Their block diagrams are shown in Figure 7, and their characteristics are summarized in Table 4. Each of the selected multiloop configurations is discussed briefly below in their nominal good configuration. Ways in which control difficulties can arise via transitions in the multiloop structures are discussed elsewhere (2).

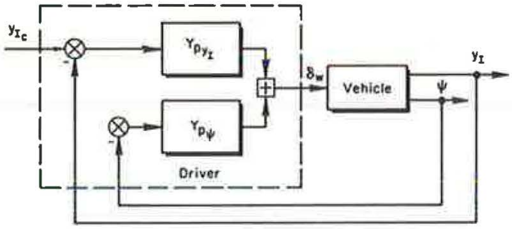
The time-advanced lateral deviation structure of Figure 7a assumes that the driver operates on an estimated or projected lateral deviation error. Preview here is explicitly required, since this error is related to the lateral position the vehicle would have at a point T seconds ahead of the vehicle if it continued along its current path (see Fig 2). The range to the point of regard is given by R, which is approximately equal to the velocity, U_0, times the time, T, to travel to that point. The time advance, T, provides a perceptual preview that results in a pure lead equalization term in the effective controlled element dynamics. This, in turn, offsets the undesirable double integration form of the lateral deviation dynamics at low frequency. When operating as described here, this system is essentially single-loop, although the multiloop aspect of Figure 7a



a) Inertial Lateral Deviation Advanced in Time



b) Path Angle Plus Inertial Lateral Deviation



c) Heading Angle Plus Inertial Lateral Deviation

Figure 7. Block diagrams for selected multiloop closures.

is useful for later studies of transitions and to make Figure 7a comparable with Figure 7b.

The amount of lead is given by R/U_0, which is under the direct control of the driver and depends simply on how far down the road he is looking. Analyses indicate that a T of 5 to 10 sec is adequate. Larger values are of little help under normal circumstances. Values of T less than 5 sec (440 ft at 60 mph) are not as good because they do not compensate sufficiently for the inherent lags in the driver/vehicle system. This system structure provides a relatively high crossover frequency and good lateral position control on straight roads. Some conceptual and analytical difficulties arise when it is necessary to follow a curving roadway or a passing trajectory; e.g., a guidance law or scheme is needed to provide an appropriately advanced command input to compare with the projected lateral deviation.

The path angle plus lateral deviation system of Figure 7b assumes that the driver operates on these motion quantities as separate entities. It differs from the Figure 7a model by having the present lateral deviation available to the driver for comparison with a desired command input and derivation of a position error. With equivalent gains the two systems are indistinguishable in the absence of a command input. Table 4 shows that the path angle plus lateral deviation system gives adequate stability and reasonably good command-following. The stability of the system is relatively insensitive to variations in the loop gains, although the crossover frequency and (hence) system bandwidth will change, of course. Consequently, the system is reasonably forgiving of momentary lapses in attention and does not require continuous control.

TABLE 4

MULTILOOP SYSTEM CHARACTERISTICS

System	Inner Loop		Outer Loop		Remarks
	Equalization	Crossover Freq. (rad/sec)	Equalization	Crossover Freq. (rad/sec)	
Inertial lateral deviation advanced in time	—	—	Gain only	1.2	Fine for straight roads. Difficult to define command input form and point of entry into the system. Sensitive to changes in preview.
Path angle plus inertial lateral deviation	Gain only	1.0	Gain only	0.53	Control not sensitive to changes in driver adaptation or driver attention. Outer loop can operate intermittently.
Heading angle plus inertial deviation	Gain only	1.5	Gain only	0.6	Control not sensitive to changes in driver adaptation or driver attention. Outer loop can operate intermittently.

The heading angle plus lateral deviation structure of Figure 7c assumes that the driver operates on these motion quantities separately and combines them to produce a steer angle response. It differs only slightly from the preceding model in its use of heading angle instead of path angle (which is heading plus sideslip) as the inner loop. Table 4 shows that the heading angle plus lateral deviation system gives good command-following and performance, is relatively insensitive to changes in driver adaptation, permits fairly inattentive control, and has the attributes needed for good driver opinion. It has the additional possible advantage that heading angle (which is simply the subtended angle between reference lines on the car and in the roadway) may be easier to perceive under certain circumstances than path angle (which is the angle between a roadway reference line and the line to the point of no relative motion in the surround). Note, finally, that sideslip angles are usually relatively small, in which case heading angle and path angle are almost the same quantity.

To avoid potential confusion about the relative merits of the three systems insofar as outer-loop crossover frequency is concerned, it should be emphasized that the larger value for the advanced-in-time system is an artifact of the loop closure criteria used. As already noted, the closed-loop dynamics of the three systems can be made very similar if the loop gain and preview times are appropriately adjusted. However, in making the estimates for the systems of Figures 7b and 7c, the inner loops are closed with relatively large stability margins, so as to be representative of conditions with possibly intermittent closures of the outer loop. The advanced-in-time system of Figure 7a, on the other hand, has no separable inner loop, so this consideration did not apply.

None of the systems shown in Figure 7 include the two feedforward channels or the discrete response feedback loop of Figure 1. This is because the closed-loop systems shown in Figure 7 are most appropriate for command-following or regulation tasks of a reasonably continuous nature with inputs that are more or less random appearing. The other types of response involving learned maneuvers, etc., are important and do dominate the driver's control activity in some phases of driving. However, the closed-loop type of control is fundamental to many other phases of driving, and plays a key "take-over role" in circumstances where the learned maneuvers and patterned responses either cannot be structured or are suddenly destroyed for one reason or another. The compensatory loops are also used in early phases of learning (the unskilled driver) and under conditions of extreme stress (the startled or confused driver). If the closed-loop systems will not or cannot work, then there is little chance that the driver/vehicle system will function safely for long. Thus, understanding their form and operation gives the point of departure for either adding the other channels or switching to them as needed.

These three systems do not exhaust the possible multiloop structures that can be concocted. Equally good candidates are similar systems containing lagged heading rate or lagged curvature, previously noted to be good inner loops. Nevertheless, these five possible multiloop systems are the only ones found to date that satisfy the guidance and control requirements for command-following and disturbance regulation with good performance, insensitivity to variations in the driver's dynamic adaptation, good predicted subjective opinion from the driver, etc. Further, they are not inconsistent with available perceptual data obtained from driving experiments on the highway. In addition to modeling the driver/vehicle system in a useful way, they can also provide a new framework for devising further experiments to study driver perception and control processes. All five structures give roughly the same performance under good conditions, although they differ in some details. The principal distinction between them lies in the way in which they degrade when the nominally good structure is disturbed. Such a disturbance might disrupt the perceptual interaction between the driver and the surround. It might also modify the driver element by distraction, inattention, or other degradation; the vehicle element in a mechanical way; or the roadway environment's texture, illumination, etc. The way in which these transient modifications in the dynamics of elements within the guidance and control loop(s) or in the loop structure itself can lead to dangerous vehicle motions is examined elsewhere (2).

Correlation With Experimental Observations

The identification of preferred driver/vehicle loop closures and sensory cues from a control theory approach provides a new framework for reviewing past perceptual experiments. The perceptual basis is somewhat fragmentary, but all the available evidence tends to corroborate the results of analytical deduction previously cited. The following verbal evidence and remarks from representative sources will at least illustrate the trend of activities in this area.

A pioneering series of experiments by Gordon (23) attempted to define the driver's visual input experimentally. The apparatus was a helmet-mounted aperture for one eye comprised of a tube 3.5 in. long with a variable diameter of 1 in. or less. The resultant aperture angles were 4 deg and 9.75 deg. The other eye was masked. A camera was mounted on the helmet coaxially with the aperture tube. The task was to drive along a narrow, winding, two-lane country road. Gordon found that most records showed continuous visual shifts forward to the limit of the visible road and then backward toward the vehicle. This bimodality of fixation positions suggests that the driver may be looking down the road to obtain heading or path angle information, and then occasionally looking near the vehicle to sample lateral position or deviation. His data also showed that about 80 percent of the time the driver was looking more than 100 ft ahead of the vehicle, while about 60 percent of the time he was looking farther than 150 ft ahead. At the test speeds of about 15 mph (20 fps) these are preview times of 7.5 and 5 sec, respectively. These times correlate well with the desirable preview time, T, found for the time-advanced lateral deviation model of Figure 7a. The use of small-aperture viewing was reported to cause stress, suggesting that denial of the peripheral cues may lead to a significant degradation in the perceptive structure.

In a more recent paper (24) Gordon expands on the "streamer theory" [after Calvert (25)], which states in essence that the driver perceives motion from objects in the visual field streaming across his field of view and emanating from a central focus (when following a nominally straight path). An alternative is taken by Gibson (26) who asserts that the "focus of expansion" provides the directional cue rather than the flow characteristics of the velocity field emanating from the focus. Regardless of how the driver senses the direction to this focus, this cue is precisely the path angle cue discussed previously. Gordon goes on to say that all parts of the visual field (road borders and lane markers) move when the wheel is turned, and no one part is essential for tracking. His studies showed that the driver may assume a somewhat unlocalized surveillance of the road, which would facilitate seeing a steady-state flow field and also reduce nystagmus. He later suggests that "the driver may become aware of the car [motion] by slewing shifts in direction, and by sideslipping sidewise movements," and "sidewise movement of the road borders is perceptible either as a movement or change in position." He concludes that "on the basis of human perception theory [alone] it is difficult to determine which of the four combinations of slew, sideslip, rate, and amplitude the driver perceives. The driver responds to a total situation, not to isolated or ranked cues."

Schmidt and Connolly (27) discuss perception in general, and then note that "the driver recognizes the movement of the car from the apparent flow or streaming of the objects in the visual field. . .", agreeing in essence with Gordon and Calvert.

Biggs (28) conjectures that in driving the central vision is occupied with the detection of obstacles in the immediate path while the peripheral vision is employed in the task of tracking the "guideline" or dividing line. He notes that "the guideline is seen near the vehicle, and its lateral motion provides the dominant directional cue." It could be inferred from this that the "directional cue" detected in the periphery from motions of the guidelines (or streamers) yields heading or path angle and possibly angular rate. Inertial deviation is, of course, just the current position of the guideline or streamer.

Crossman et al (29) hypothesized a family of more or less distinct control systems or modes of driver control, and tested them by comparing driving performance in a fixed-base simulator with that obtained under actual driving conditions on the highway. They showed better performance on the highway, and several subjects claimed that the simulator was more difficult to control than an actual vehicle on the roadway. The differences were potentially attributed to the visual display, lack of motion cues, and deficiencies in the simulated vehicle dynamics. Examination of the time records suggested that the driver apparently responded in an impulsive way to heading (or path angle) errors when they exceeded a threshold level.

Even though these references are all fairly recent, none of them specifies the alternative closed-loop structures appropriate to various driving situations. They do support, however, a theory of driver control derived from guidance and control considerations. While there are apparent differences between these experimental results, some semblance of order is obtained by viewing them within a guidance and control structure, and the operational entities extracted from the perceptual cues do provide the prescribed feedbacks.

SOME IMPLICATIONS OF THE APPROACH

The objectives of the research of which this paper forms a part have been to gain further understanding of driver control processes, and to determine why guidance and control errors occur and how they can be avoided to reduce the hazard. The major results of the first objective have been presented here. These have involved the derivation and development of operational models for the driver/vehicle/roadway system that use the techniques and principles of feedback control theory. The resultant analytical tools can be used to determine the role of the various elements (driver, vehicle, etc.), to determine how they interact, and to assess the effect of changing system parameters.

The study of guidance and control errors and their avoidance has been accomplished (2) by applying the driver/vehicle closed-loop models. The following general problem areas were considered:

- Transitions in the driver/vehicle/roadway system, with emphasis on sudden changes in the perceptual structure and their varying degrees of resultant hazard. Examples included loss of driver preview, failures of the path angle inner loop (while retaining the lateral deviation loop) at various points during a passing maneuver, and loss of the heading angle inner loop followed by introduction of driver lead equalization in the lateral deviation outer loop.
- The effect of acceleration feedbacks, with emphasis on ways they can interfere with good visual loop structures. The influence of driver location (relative to the center of the vehicle) on the acceleration cue, and transitions from visual control to steering control based on accelerations at the usual position of the driver's head were studied. Inadvertent steering inputs due to arm/hand inertia of the steering wheel (in the presence of vehicle accelerations) were examined.
- Highway gust disturbance inputs, with attention to the types of highway gusts that can be most troublesome and how they can arise. The open-loop (steering wheel fixed) and closed-loop gust response dynamics were computed. Step and pulse crosswind inputs were modeled, and these were used to compute transient time responses of the driver/vehicle system both open- and closed-loop.
- Steering system dynamic lags, and their significance to the closed-loop characteristics of the combined driver/vehicle system. Preliminary data were cited to show that steering lags may be as large as the driver's effective time delay. Since these delays are additive, the bandwidth and performance of the driver/vehicle system will be reduced accordingly.

The approach to these problems involved examining good driver/vehicle control structures to see ways in which they might be degraded, and looking at poor situations to see how they might be improved or avoided. Many of the control concepts used (such as the adverse effect of opening an inner loop) are not new to a controls engineer, but it is their application to understanding the guidance and control of automobiles that represents an innovation.

The study of driver control during overtaking and passing (2) resulted in recommendations regarding driver, vehicle, and roadway. Those of particular interest to the highway engineer involve the following topics:

- Geometry and marking of passing zones,
- Crosswinds and highway gusts,
- Relation of speed and sight distance, and
- Enhancement of perception and control with texture and contrast in the surroundings.

Specific amplification of existing policy (30) has resulted with regard to the first two topics. For the latter two, existing policy and guidelines have been corroborated but not yet extended to a significant degree. These recommendations are discussed below. Although the analytical results are clear, they must be considered tentative until they have been substantiated by experiments involving operating conditions on the highway.

Passing zones should be standardized so that the driver is confronted with one of a small number of familiar visual patterns and driving tasks when a passing situation occurs. Ideally, such standardization would evoke a learned response pattern from the driver, thereby enhancing performance and improving safety and throughput. Standardization might be achieved with respect to such areas as roadway marking, lane width, length of passing zones, signs, lighting, and crown. Distraction of the driver and disturbance of the driver/vehicle system should be minimized in overtaking and passing zones, particularly during the most critical pull-out and pull-in phases. Any necessary and intentional distractions (e. g., signs) should require a total attention time of less than about 2 to 3 sec and should not occur during those parts of the zone where pull-out or pull-in is most likely to occur. The policy on passing zones should consider weather conditions and adverse visibility in order to avoid being either overly conservative or too hazardous. Utilization and safety could be better optimized by distinguishing (for example) between day and night or wet and dry conditions in the design criteria, perhaps permitting additional zones to be established. The resultant restrictions might be placed on a sign at the start of the passing zone.

Crosswinds and highway gusts can have an adverse impact on a moving vehicle and result in degraded performance. Structures near the roadway, alternate cut and fill sections, forested and cleared sections, etc., can all cause significant "pulse gust" inputs to the moving vehicle in the presence of a strong crosswind. Pulse durations of 1 or 2 sec cause the greatest disturbance to automobiles and small utility vehicles (e. g., campers and vans), where the duration is estimated by dividing the width of the obstruction normal to the crosswind by the vehicle's speed. An automobile overtaking and passing a truck or bus in a crosswind can experience a similar pulse gust disturbance, and a high overtaking speed can result in a critical pulse duration. This may suggest the desirability of wider lanes or separation of truck and automobile traffic in areas of known crosswind problems. Ways of alleviating the gust pulse disturbance through highway design involve either eliminating the source or modifying it to make the pulse onset more gradual than an abrupt wind shear. This might be accomplished by moving structures away from the roadway and allowing pulses to dissipate, adding plants or small objects at the end of obstacles to break up the air flow and cause a more gradual shear, tapering objects to the ground rather than squaring them off vertically, etc. Attention should also be given to possible highway gust problems in route selection, and if a route is selected where this may be a problem, alleviation should be specified in the design. This is particularly true in recreational areas (e. g., mountains and deserts) where campers and trailers may comprise a large percentage of the traffic.

Adequate sight distance for a given speed is important in driver steering control, but the distances required are compatible with the "minimum stopping sight distance" currently prescribed (30). The guidance and control need for sight distance should be borne in mind if reducing the minimum stopping sight distance is contemplated, due perhaps to evolutionary improvements in braking systems. The considerable attention given in current policy to adequate texture and contrast of the median and shoulder is supported by this study. This includes different colors or shades, striping, guide posts, etc.

Remedial actions involving the vehicle relate to the general area of handling and specific cases and situations have been treated in considerable detail using this analytical approach. The analyses also lead to visibility implications involving improved windshield framing, visual reference lines on the vehicle, etc.

Regarding the driver, a recurrent theme is the importance of appropriate driver training and skill development. In some cases this may involve the use of unconventional training techniques that explore limiting driving situations in a systematic way in order to provide the student a minimal level of familiarity and skill. Such situations might include overtaking and passing on rural roads, entry onto high-speed expressways, and skidding on slippery roadways (e. g., with a sandy or icy skid pad at low speed).

These implications and brief examples serve primarily to illustrate the utility of a control engineering view of the driving process. In essence, a new capability has been established that can guide the highway systems engineer in his efforts to improve the driver/vehicle/roadway system, or to assess the effect on vehicle control of proposed changes that may be thrust upon him. Although not a panacea, the approach provides fresh insights, some alternative views to the traditional, a basis for interpretation of experimental results, and a useful foundation for designing new driver control experiments that can more fully validate the theory. Application of the derived models can provide the basis for remedial action that can help to avoid control difficulties or enhance the guidance and control situation and increase traffic throughput.

CONCLUDING REMARKS

The original version of the paper, presented at the 47th Annual Meeting, contains an Appendix that details the multiloop analyses leading to the results of Table 4. This Appendix is available at cost of reproduction and handling from the Highway Research Board. Essentially the same material is contained elsewhere (Appendix D, 2). When ordering, refer to XS-23, Highway Research Record 247.

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Drivers' Eye Movements: An Apparatus and Calibration

THOMAS H. ROCKWELL, C. OVERBY, and RONALD R. MOURANT,
Systems Research Group, The Ohio State University

A description is given of a portable eye-marker camera and a specially designed stablization unit that may be used to record drivers' eye movements. A pilot study was conducted that showed that drivers' eye movements are closer in toward the vehicle under night driving than day driving. The pilot study also pointed to the need to examine the calibration accuracy of the system. In Phase I of the calibration experiment, seven drivers served in a 2 × 2 × 2 within-subjects design. The three independent variables were head movements (calibration before vs calibration after), distance (30 vs 60 ft), and sessions (Day 1 vs Day 2). Sessions were investigated to see if subjects can be calibrated with the same accuracy on different days. In Phase II of the experiment, calibration accuracy was measured before and after the subjects drove an automobile. Calibration accuracy was measured by having the drivers trace a matrix of targets that covered the field of view of the camera. Error was defined as the distance from the center of the target to the center of the eyespot. Analyses of variance showed that head movements, distance, and sessions had no significant effect on calibration accuracy. The effect of driving on calibration accuracy was small. The average calibration error for all subjects under all conditions was ±1 degree. Potential uses of the eye-marker camera in driving research are discussed.

•AN automobile driver receives more information from his eyes than through any other sensory modality. Knowledge of the visual behavior of drivers may lead to the identification of stimulus cues used in driving, promote the development of measures of driver work-load and fatigue, and provide data for the design of driver aids and route information systems. Although eye-marker cameras have been used in laboratory situations for many years, their use in dynamic environments has been hindered by equipment and calibration difficulties. The recent development of portable head-mounted units and a new stabilization technique has overcome these difficulties.

APPARATUS

The apparatus for recording drivers' eye movements consists of a Polymetric Products eye-marker camera (model V-0165-1L4) used in conjunction with a stabilization unit developed by the Systems Research Group (Fig. 1). The input system (Fig. 2) consists of a scene lens, an eye lens, and a light source. The light source is a 6-volt, 0.3-amp miniature bulb powered by a 9-volt battery. The eye lens monitors the corneal reflection of the light source and reflects it into a fiber optic cable. The scene lens has a 20 deg field of view in both the horizontal and vertical planes. The field-of-view is reflected into a second fiber optic cable. The image-transmitting fiber optic cables are 4 ft in length and have a resolution of 40 lines per mm.

Paper sponsored by Committee on Road User Characteristics and presented at the 47th Annual Meeting.

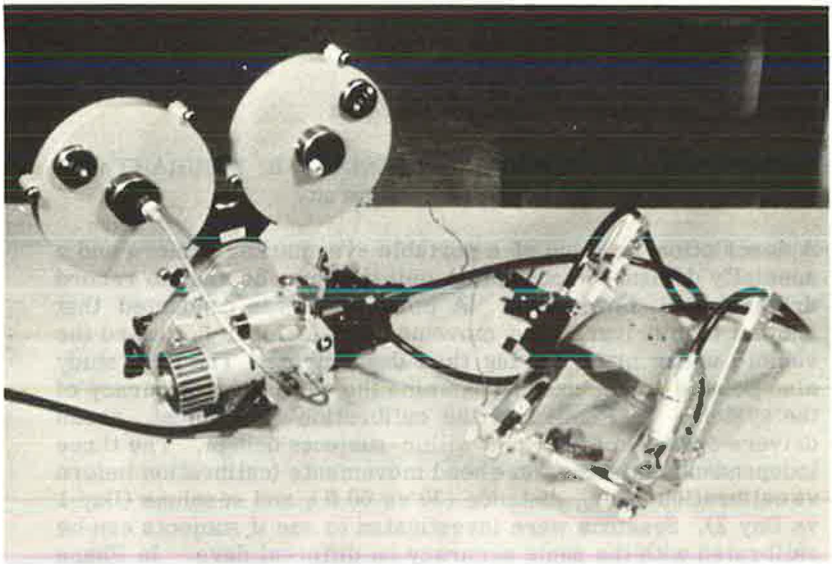


Figure 1. Eye-marker camera and stabilization unit.

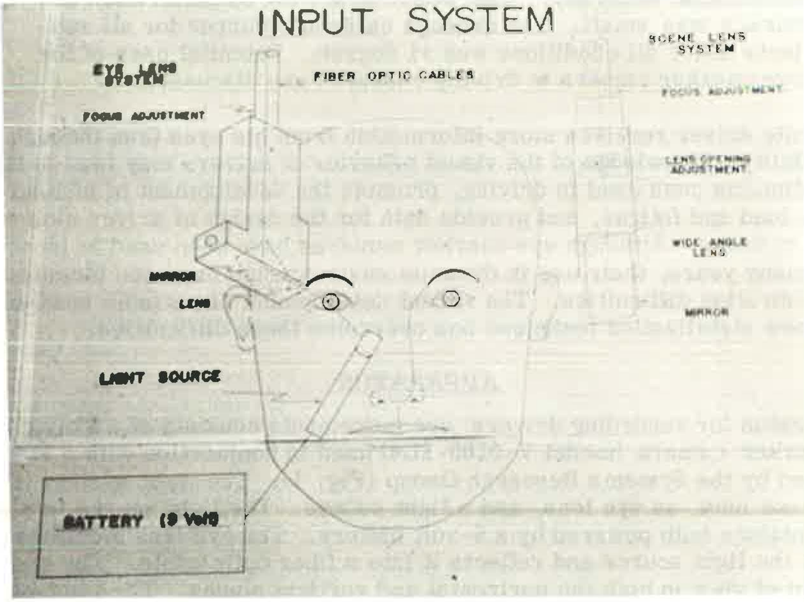


Figure 2. Input system.

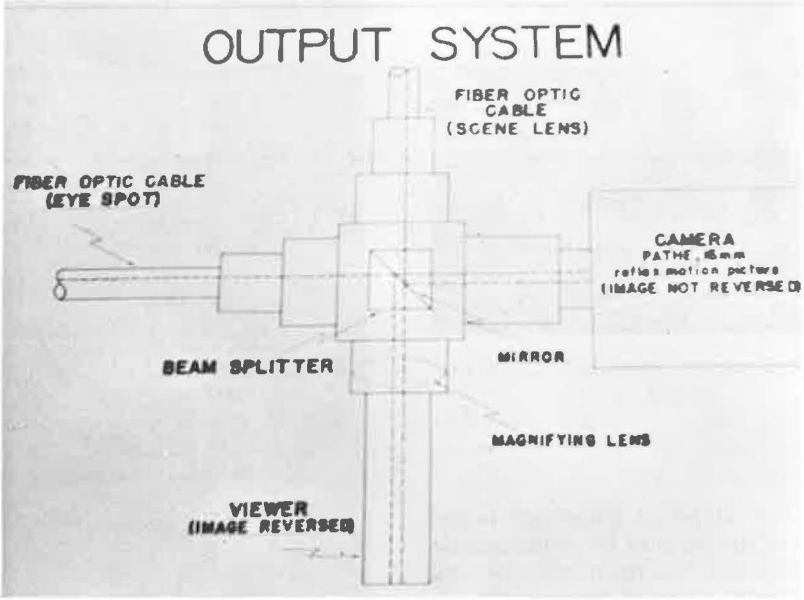


Figure 3. Output system.

The output system (Fig. 3) consists of a beam-splitter, a 16-mm Pathé camera with associated electric motor drive, and an auxiliary viewing device. The beam-splitter optically combines the images from the fiber optics cables that come from the scene lens and the eye lens. This enables the camera to photograph the eyespot when it is superimposed on the field of view. Since the fiber optic cables have a light loss of about 80 percent, Kodak Tri-X Reversal Film (type 7278) was used for daylight photography. A high-speed film, Kodak No. 2475, was used for night photography.

The stabilization unit (Fig. 4) consists of an individually fitted helmet, side-support brackets, a pressure bar that extends between the brackets, and a mouthpiece that fits against the upper teeth only. Four adjusting screws between the brackets and the pressure bar permit the subject to adjust the pressure of the unit between his upper teeth

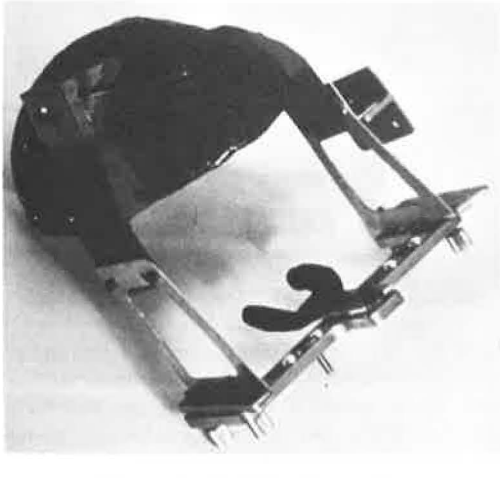


Figure 4. Stabilization unit.

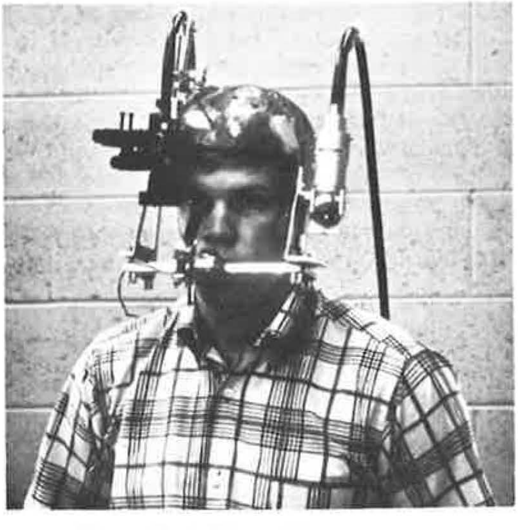


Figure 5. Subject with apparatus.

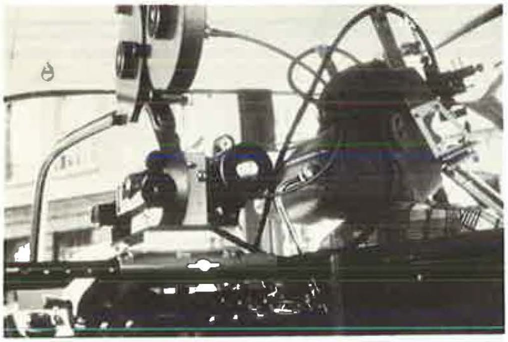


Figure 6. Eye-marker camera and subject in vehicle.

and head. The subject's lower jaw is unconstrained, allowing him to communicate verbally. The unit has been worn as long as 3 hr with little signs of discomfort.

A subject with the apparatus on is shown in Figure 5. The subject and the eye-marker camera mounted in the test vehicle are shown in Figure 6.

PILOT STUDY

The first pilot study using the Polymetric eye-marker camera studied driver eye movements on two highway test sections under both day and night conditions. One highway test section was a 22-ft rural two-lane highway (Ohio 315) having a painted dashed centerline but no white edge line. The other section was a four-lane divided highway (US 23) having an ample median strip and a white edge line.

In order to better relate the eyespot to highway detail at night, two fixed reference lights were placed on the automobile for both the day and night data runs. Knowing the spatial location of these lights and the position of the driver's eyes, it was possible to approximately project the eyespot to a particular highway feature even though road features were not visible on night film. A sample of the data collected is shown in Figure 7. To facilitate data analysis, part of the driver's visual field was divided into seven sections, as indicated in Figure 8. These seven sections were chosen so as to contain prominent highway features that were believed to be significant sources of information for the driver in controlling his vehicle.

Figure 7. Six frames from 16mm data film taken under day conditions. The two bright spots spaced about ½ in. apart in each frame are the hood reference lights; the relatively unfocused larger white spot near the right hood light is the eyespot.

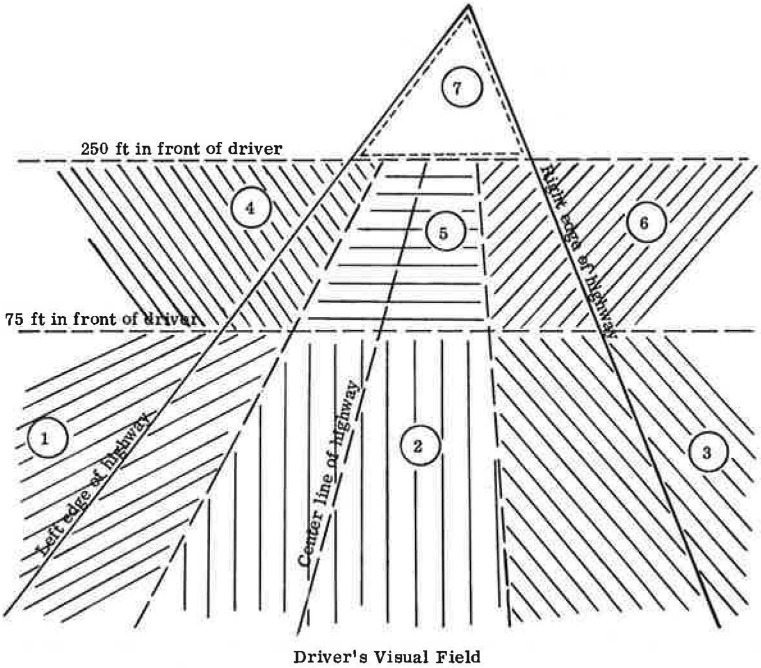


Figure 8. The seven areas used in data analysis.

One aspect of this study concerned the percent of time the eyespot was in each of the seven sections. The results indicated that for both highway test sections the areas of fixation for night driving are closer in front of the vehicle than for day driving. Table 1 gives percent of fixation duration as a function of the distance in front of the vehicle for day and night driving and for two-lane and four-lane highways.

It was found that the areas of fixation for the rural two-lane highway are closer in front of the vehicle than for the four-lane divided highway. The film also indicated that the center and edge road markings are used differently by drivers in day and night conditions. At night, more use is made of the right edge marking and at distances closer to the vehicle than in daylight driving. Thus, the data suggest that highway marking systems are a greater aid in controlling a vehicle under poor visibility conditions than in normal daylight driving.

Because this was a pilot study and data were collected for only two subjects, no statistical analyses were made on the results. However, the study made it clear that driver eye movements are reflectors of different driving situations. This study also brought out the need to determine the calibration accuracy of the eye-marker camera.

TABLE 1

PERCENT FIXATION DURATION AS A FUNCTION OF DISTANCE FOR DAY AND NIGHT DRIVING AND FOR TWO-LANE AND FOUR-LANE HIGHWAYS

Distance	Day Driving	Night Driving	Rural Two-Lane	Divided Four-Lane
0-75 ft	0	9.5	0.5	1.3
75-250 ft	9.2	17.9	19.9	8.0
>250 ft	70.0	25.4	53.6	44.8
Other	21.8	52.8	25.0	45.9

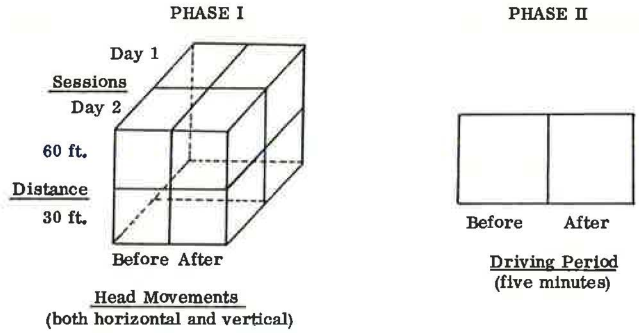


Figure 9. Experimental design of the calibration study.

CALIBRATION STUDY

Recently, Mackworth (2) reported the registration accuracy of a stand-mounted corneal-reflection eye-camera to be ±1 deg. Registration accuracy is the precision with which the eyespot (the reflection of the light source off the cornea) corresponds with where the subject is actually looking. An eye-camera is calibrated when the registration accuracy for any point in the visual field is less than ±1 deg. Other investigations (1, 3) have reported that subject head movements caused loss of calibration accuracy. Williamson and Barrett (3) also reported that registration accuracy varied as a function of the distance of the target to the subject's eye. The experimental design of the calibration study is shown in Figure 9.

In both Phase I and II all subjects served in all conditions. The subjects were seven male Ohio State University students ranging in age from 19 to 29. They were given a vision examination by the School of Optometry, and all were found to have normal visual health and at least 20-30 uncorrected vision.

At the beginning of each session the eye-camera was calibrated on the subject in the laboratory. The subject drove the vehicle (1963 Chevrolet) to the test site where he positioned it in front of a 2 × 3 target array (Fig. 10). The distance between target centers in the horizontal plane spanned 17 deg and in the vertical plane 8 deg, 30 min. Since the vehicle's hood prohibits the driver from looking down at this angle, it was impossible to span 17 deg in the vertical plane. Therefore, only a two-row target array was used. Film was collected while the subject's eyes traced the matrix twice for each experimental condition in each session.

Registration error was defined as the vertical and horizontal components of the distance from the center of a target to the center of the eyespot. Sign conventions for the scoring of errors are shown in Figure 11.

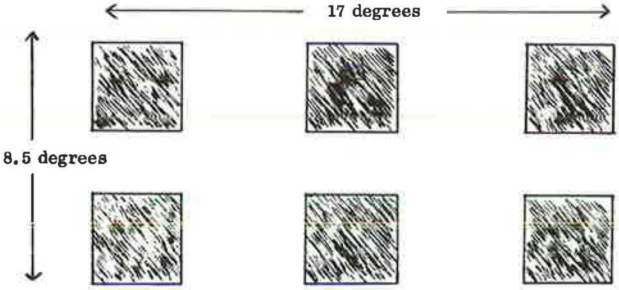
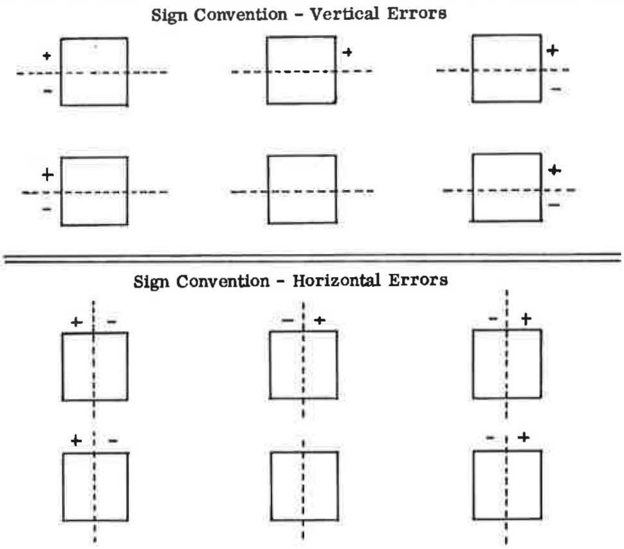


Figure 10. Target array.



Sign Convention - Vertical Errors

Sign Convention - Horizontal Errors

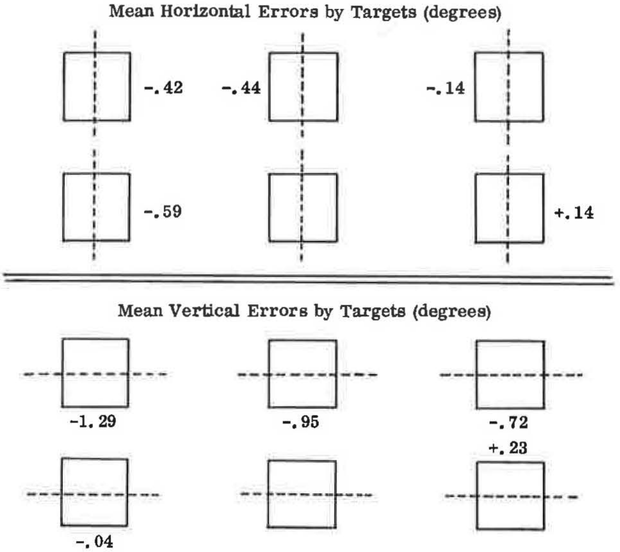
Figure 11. Sign conventions.

Errors were measured by examining the film frame by frame. A computer program converted the error measured in inches into degrees in order to make comparisons between the two distances and all targets.

Pearson product-moment correlations between the vertical and horizontal errors for each target were not significant, indicating that the horizontal and vertical errors may be analyzed separately.

Calibration Results

The mean vertical and horizontal errors are a function of target location. When summed over all experimental conditions, they are an indication of the calibration accuracy of the eye-camera. In Figure 12, the mean vertical and horizontal errors are



Mean Horizontal Errors by Targets (degrees)

Mean Vertical Errors by Targets (degrees)

Figure 12. Mean vertical and horizontal errors of calibration—Phase I.

TABLE 2

MEAN HORIZONTAL AND VERTICAL ERRORS—PHASE I

Variable	Horizontal Error (deg)	Vertical Error (deg)
Subjects		
1	-0.52	-0.93
2	-0.27	0.08
3	-0.20	-0.54
4	0.20	-0.85
5	-0.60	-0.64
6	-0.29	-0.47
7	-0.33	-0.52
Sessions		
Day 1	-0.29	-0.52
Day 2	-0.28	-0.59
Distances		
30 ft	-0.26	-0.57
60 ft	-0.32	-0.53
Head movements		
Before	-0.31	-0.51
After	-0.26	-0.59

TABLE 3

MEAN HORIZONTAL AND VERTICAL ERRORS—PHASE II

Variable	Horizontal Error (deg)	Vertical Error (deg)
Subjects		
1	-0.63	-0.94
2	-0.23	-0.85
3	-0.32	-0.56
4	-0.03	-0.42
5	-0.57	-1.19
6	-0.28	-1.02
7	-0.41	-0.57
Driving		
Before	-0.26	-0.63
After	-0.44	-0.96
Targets		
Lower left	-0.59	-0.11
Upper left	-0.31	-1.53
Upper center	-0.56	-1.22
Upper right	-0.31	-1.03
Lower right	0.02	-0.08

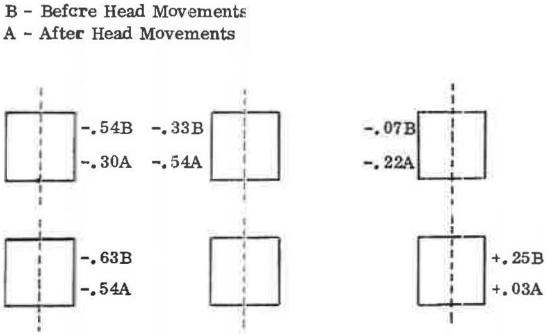


Figure 13. Interaction of head movements and targets.

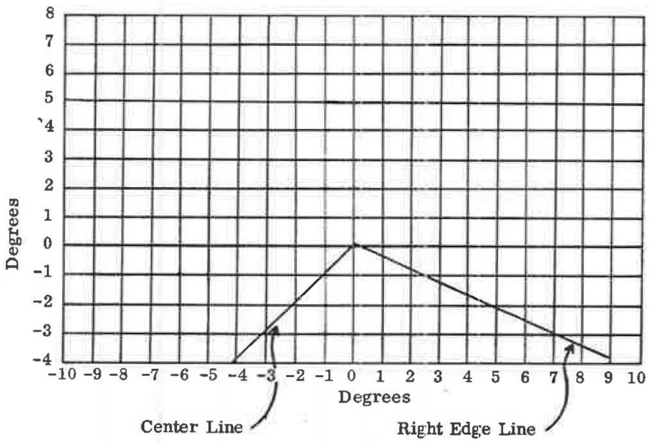


Figure 14. Data-reduction grid.

shown as a function of targets. Except for one target all the horizontal errors were less than 0.50 deg. Mean vertical errors for the two targets at the driver's eye level were less than 0.25 deg. Table 2 gives the mean horizontal and vertical errors for subjects, sessions, distances, and before and after head movements.

An analysis of variance of the horizontal errors showed that the targets by head movements interaction were significant ($p < 0.01$). The main effects of sessions, distances, and head movements were not significant. The interaction of targets and head movements is shown in Figure 13. Head movements caused calibration accuracy to move slightly to the left on all targets. This effect was small and of no practical significance.

In the analysis of variance of vertical errors, targets were significant ($p < 0.01$). Sessions, distances, and head movements were not significant. The errors of the targets in the upper row were much larger than the errors of the targets at the driver's eye level.

Table 3 gives the mean horizontal and vertical errors for Phase II. The analysis of variance for horizontal errors showed no significant effects. The only significant effect in the analysis of variance of vertical errors was targets ($p < 0.01$).

In summary, head movements, distances, sessions, and driving had very little effect on calibration accuracy. In the horizontal plane, calibration error was half that in the vertical plane. Even though the subjects were in a dynamic environment, and their heads were unconstrained, the calibration accuracy of the eye-camera system was comparable to that found in most laboratories where the subject's head is held stationary. The results may partially be attributed to the stabilization unit developed by the Systems Research Group.

RESEARCH POTENTIAL

Following the calibration study, the Systems Research Group collected eye movement data of drivers in car-following, open road, traffic, and overtaking situations. Figure 14 shows the data-reduction grid used for this experiment. The system is based on

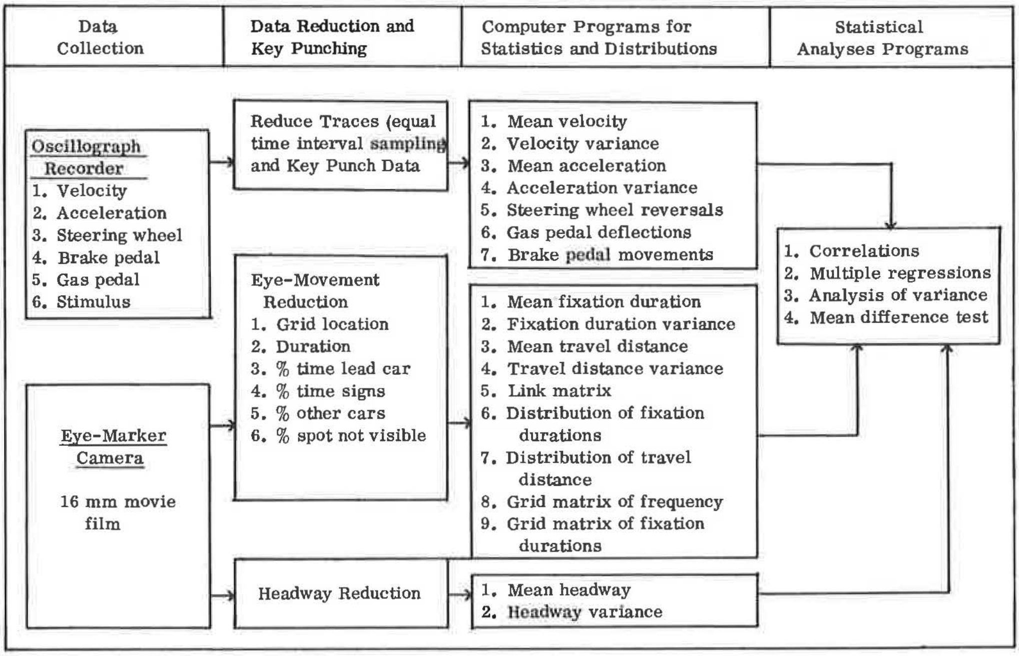


Figure 15. Data-reduction system.

lining the road geometry (the middle and right-hand marker lines) on the film with the road geometry on the data-reduction grid. This procedure eliminates the effects of driver head movements and vehicle dynamics from data reduction.

The total data-reduction system is shown in Figure 15. The reduction of eye movements from film is accomplished by using a Kodak Data Analyzer Projector. After the data are keypunched, computer programs calculate the statistics and distributions, and perform statistical analyses.

This study will provide eye-movement data that will serve as a standard for data collected in various stressful situations. Eye-movement data collected during fatigue and glare driving conditions may provide insights for the development of aids and techniques to combat these situations. In addition, the changes in eye-movement patterns while a person is learning to drive may lead to the teaching of optimal search and scan patterns for driving an automobile.

ACKNOWLEDGMENT

This work was sponsored by the State of Ohio Highway Department, the Bureau of Public Roads, and the National Cooperative Highway Research Program.

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3. Williamson, T. R., and Barrett, G. V. Feasibility of Measuring Eye Movements in Real-World and Simulated Driving Situations. Perceptual and Motor Skills, Vol. 23, p. 331, 1966.

Discussion

DONALD A. GORDON, U.S. Bureau of Public Roads—Rockwell and his collaborators are to be congratulated on their achievement in registering driver's eye movements. All of us who have attempted such measurements are aware of the difficulties that must be overcome. First there is the jounce of the moving vehicle, which throws measurements off-calibration. This problem was solved by use of a specially designed stabilization unit that was fitted against the upper teeth. Then there is the problem of precision. An error of 0.25 deg in the vertical dimension, which is the experimental accuracy achieved by Rockell et al, covers a distance from 75 to 99.4 ft ahead of the car. This precision is adequate for many purposes. The problem of field calibration was met by the development of a special device. We would like to know where the calibration array was placed and how the driver's eye was held steady during the calibration process. We have questions, too, about the use of illuminated reference spots as a substitute for night highway features. The angle of these lights relative to the road varies as the driver moves his head. But these are minor points which detract in no way from Rockwell's achievement.

With regard to driving, the traditional role assigned to eye-fixation data is that of indicating the object on the highway responded to when the driver steers, brakes, or accelerates the car. This stimulus-object stands in causal relation to the driver's response. Those of us who have attempted to identify the driver's visual stimuli have encountered several difficulties.

In the highway situation, the driver often responds to a general situation, rather than to an object in the center of his fixation. For example, he may slow up in urban traffic without leaving an indication of the cause on the eye record. It is also clear that the response may be to the driver's intention, desire, set, or to what psychologists call the organismic state. Let us suppose that the driver intends to leave a multilane highway and moves over to the right lane. In this case, the stimulus, if it can properly be called such, would be in the driver's mind, and not on the road.

As has often been pointed out, the driver can look without seeing, and conversely, he can see without looking. An object may be focused directly on the fovea, but that does not guarantee that it will be registered by the brain. Considerable evidence exists to indicate the importance of peripheral vision in driving. Unfortunately, we do not have a direct communication channel to the driver's brain to tell us what objects in the central or peripheral vision are being registered.

These difficulties have tended to discourage the interpretation of eye-fixation records. As we view the driver's eye, directly or on a film record, it darts back and forth, lighting in seemingly random fashion on conspicuous objects in the field ahead. The confusion is compounded when we remember that while the eye is roving ahead, the driver's hand is controlling the vehicle in relation to a different, and past situation. For example, the hand may be guiding the car out of a curve, while the eye is running ahead and exploring the next curve.

This situation is not as discouraging as it appears; eye fixation data have a clear meaning, based on the role of vision in the highway situation. Despite the apparent confusion, a very well-organized operation is taking place. The movements of the eye serve the driver's need to obtain information required to deal with the situation. Under conditions of limited visibility, as in rain, fog, or lowered illumination, every fixation counts, and if the essential information is not obtained, the driver will slow down or halt. Under daylight illumination, on a straight, uncluttered road, the required information is easy to obtain. In this situation, the eye may become lazy and spend considerable time on irrelevant objects, and may even indulge in looking without seeing.

The position that the eye's role is to gather essential information is quite different from the old visual stimulus interpretation. The driver is not to be regarded as a football kicked about by stimuli in the visual field. Rather, he is the executive who actively directs the search for information required for planning ahead. The relevant research

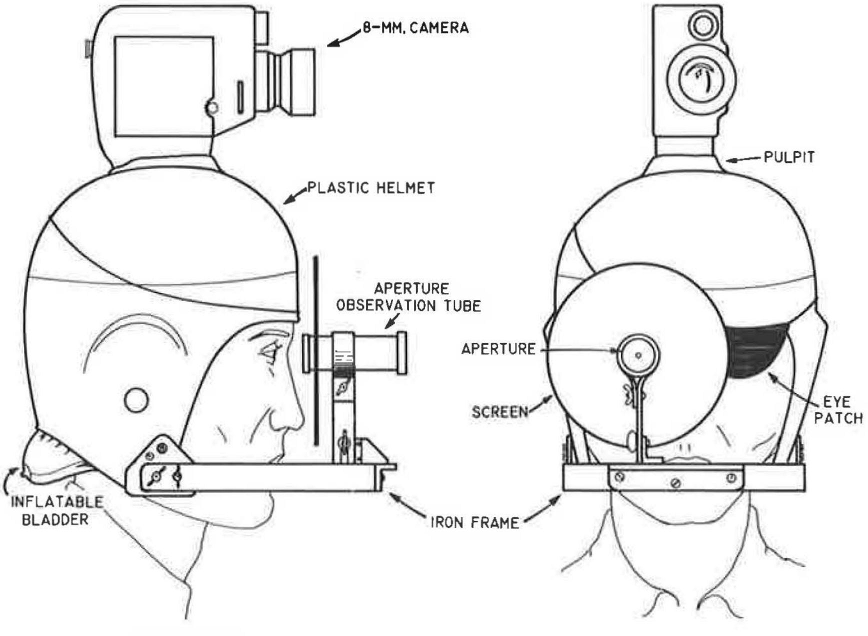

Figure 16. The apperture device. The apperture is fastened to a helmet with camera on top. The other eye is occluded with a patch. An inflatable bladder fills the space between the head and helmet.

questions then become: What is the essential information required for various maneuvers? What are the typical modes of information-gathering used by the driver? Under what conditions is essential information missed and an accident-prone situation created? We are led to develop techniques for quantifying information and to study problems of information-processing and overload.

For indicating essential information, techniques other than eye-movement recordings may be used. In a previous paper (4), I have discussed a technique for isolating the driver's essential information. The method involves having the driver guide the car while looking through a device containing a small aperture (Fig. 16). By decreasing the visual field, the essential information, whatever it is, cannot be seen at once; i.e., the driver is forced to obtain this information in separate visual fixations. A continuous film record is made of his visual aim and the content of each fixation. The essential information he is using is easily identified in each separate restricted fixation. The stimulus to driving may also be studied by formal experimentation. For example, Michaels and Cozan showed that the sideways angular velocity of an approaching object in the field of view could logically be considered a stimulus to lateral displacement of the vehicle by the driver. Introspective data should not be neglected. Information becomes essential only in relation to the intentions and purposes of the driver. To the extent that the driver is aware of what he is looking at and trying to do, introspective data may explain his response.

Eye-fixation data are likely to have their most important application regarding the question of how the eye secures essential information. In maneuvers such as overtaking and passing, lateral displacement to a road obstacle, merging, and braking, we can often designate the relevant stimulus, but the details of visual performance require clarification. Eye-movement data tell us when the driver starts to look, how long he looks, and in what direction. For example, in the merging maneuver, where the driver must find a gap in the main stream, eye-movement records tell us how far he looks to the side of the road and assist us to assess the danger of the task. The essential information is apparent from the logic of the situation.

Finally, in discussing the contributions of eye-movement techniques, it should be mentioned that these records have always had something special and surprising about them. Ninety years ago, Javal, an optometrist, watched the eye of a reader and found that it proceeded in jumps rather than moving smoothly across the page. Javal called these movements "saccades," which is French for "jerks." The term is still in use. The subsequent history of eye movement research has revealed many other interesting facts of visual behavior. It is to be hoped that the typical patterns of eye fixation will indicate much concerning the dynamics of the driving process. We look forward to further contributions from the Systems Research Group of the Ohio State University, now that the basic techniques have been mastered.

Reference

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T. W. FORBES, Department of Psychology and Highway Traffic Center, Michigan State University—The study of head and eye movements in driving is of considerable importance and has not been given sufficient research attention. The authors are to be complimented on developing a new combination of camera, head-mounting frame, and fiber optics for transmitting a picture, using some "off the shelf" equipment and adding or modifying it. This apparatus offers the advantage of a relatively light head-mounted unit compared with others on which the camera itself is mounted on the head frame.

The authors' combination of a pilot study using the camera in actual driving and also a calibration study to determine the recording accuracy is a desirable approach. It would seem that good accuracy was achieved.

Accuracy of calibration was not significantly disturbed when checked before and after head movements and the lateral range of eye movements was about 17 deg. This represents about one lane width either side of the median at 100 ft. If so, this appears to limit eye-movement recording to open-road driving, and information of this type is certainly needed for studying the detail of open-road driving performance.

The report does not mention the procedure for measuring eye movements when combined with head movements. Such measurements would seem to be possible with the equipment, and perhaps discussion of them was omitted for simplicity in the description. Measurement of extent and time duration of head and eye movements separately and together is highly desirable.

Important as it is, the study of detailed head and eye movements in open-road, straight-ahead driving is only the beginning of a broad area that needs to be studied.

When the 20-deg cone of clearest vision (10 deg either side of center of the fovea) is diverted off the road, the driver momentarily loses clear vision of what is ahead. During eye movements from one fixation point to another, clear vision is also lost. Furthermore, attention is usually given to the clear vision field and is less often given to stimulus objects in the remaining blurred vision areas. Thus, drivers are effectively blind or partially blind to areas out of the field of clear vision. A pilot study some years ago at UCLA indicated that drivers may be "flying blind" for significant time intervals and that these occurred not singly but in a continuous series. Times were long enough for serious things to happen. Car instrumentation and photographic recording was used. The equipment did not allow completely satisfactory measurement, but records on five subjects did indicate head movements of as much as 45 to 65 deg and a continuing series of "blind" intervals of 1.0 to 2.5 sec and more. This is an area of important information needed to understand and reduce driving hazards. The type of equipment described by the authors may well contribute in an important way to research in this area.

THOMAS H. ROCKWELL, C. OVERBY, and R. R. MOURANT, Closure—As pointed out by Dr. Forbes, the apparatus does not measure head movements. However, it does record where a subject is looking regardless of his head position. For example, if the driver is looking at the car in front of him and then turns his head 5 deg and continues to look at the car, the system can record this. There is little doubt that the measurement of head movements, in addition to eye movements, is an important goal. Dr. Gordon's question as to the use of illuminated reference spots as a substitute for night highway features is well founded. Since the angle between the subject's head and the reference lights changes with head movements, error is introduced into the determination of the eyespot location. Because of this, we have decided to use the middle and right-hand edge markers as reference lines. The location of the eyespot with respect to the edge markers is independent of the position of the vehicle and the driver's head.

The driver's eye was not held steady during the calibration process. He was instructed to fixate on the center of each target. This means that small saccadic movements of about 2-10 min of arc may have influenced the measurements. The calibration array was placed on a blank outside wall of a building.

The question of looking without seeing has been of interest for many years. Gaarder (5) reported that eye movements patterns are dependent on whether or not the subject is paying attention. Eye movements during inattention are characterized by infrequent saccades and shifting phase relationships between horizontal and vertical movements. During attention, eye movements contain about 0.3 saccades per sec with no shifting phase relationship between horizontal and vertical movements. Thus, there is hope that eye-movement patterns are reflective of the attention-inattention continuum.

Both reviewers have addressed themselves to the problem of interpretation of eye-marker data. In a study currently being conducted at Ohio State University, preliminary results show that mean duration of eye fixations in the traffic condition is lower than in the open-road driving condition. This indicates that statistics from eye-marker data may be a measure of driver work load.

Reference

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Drivers' Decisions in Overtaking and Passing

DONALD A. GORDON and TRUMAN M. MAST, Traffic Systems Division, U.S. Bureau of Public Roads

Drivers' estimations of overtaking and passing distance were compared with actual overtaking distance. Drivers made estimates in a familiar car and in an unfamiliar car, at speeds of 18, 30, and 50 mph. Conclusions were as follows: (a) Drivers were unable to estimate overtaking and passing distances accurately. Mean error ranged from 20 to 52 percent of performance distance. Significantly larger errors were made in the unfamiliar vehicle than in the driver's own vehicle. (b) Negative errors of underestimation, where the maneuver required more space than judged, increased with speed. At 50 mph, 60 percent of the estimates made by drivers in the unfamiliar car, and 78 percent of those made in own cars were underestimations. (c) Overtaking and passing required proportionally more distances as lead car speed increased. (d) Vehicular differences affected passing distance more than did driver variance.

•ON a two-lane rural road, the driver must often overtake and pass a car in order to maintain pace. While many studies have been made of this maneuver, little is known about the driver's decision processes, although the driver is the essential element upon whose judgment the safety of the passing performance depends.

To overtake and pass, the driver must carry out the maneuver in the time or space available. Based on this requirement, the maneuver may be analyzed in terms of four basic quantities:

α is gap time or distance separating the overtaken and opposing vehicles.

α' is the driver's estimate of gap available.

β is the time or distance required by the driver-car combination to perform the maneuver.

β' is the driver's estimate of time or distance required to perform the maneuver

The driver's judgment in overtaking and passing involves a comparison of α' and β'. (The prime notations involve psychological characteristics, which are distinguished from physical variables.) If the outcome is favorable, i.e., the gap available, α, is judged to be longer than the distance required, β, with adequate safety margin, the driver will accept the gap. If not, he will reject it, and wait for a longer gap. With practice, the gap decision becomes habitual and is rapidly made.

The $\alpha\beta$ concept also applies to the driver's gap judgments in merging and in passing an intersection and to other driving decisions as well. When the driver makes a U-turn, the width of the road, α, is related to the turning radius of the car, β. In parking, the driver compares the parking space with the width of the car plus the room required to open the doors.

Both α and β are measured in physical units of time and distance; α' and β' are also measured in physical units, but these quantities are obtained in psychological experimentation. Silver and Bloom (8) measured α' gap size by asking drivers to indicate the

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distance when an opposing car was just 12 sec away; β' may be measured by having the driver indicate the minimum distance at which he can just perform the maneuver. Whether time or distance is used to measure the gap depends on the application. Time is the usual measure of intersection gaps (9, 10), but both time and distance have been used in overtaking studies (1, 8).

PREVIOUS STUDIES

The literature on overtaking and passing has been reviewed by Farber and Silver (2). Early studies were concerned mainly with establishing performance norms for traffic control. Matson and Forbes (5) and Prisk (6) give figures on overtaking distance when the pass was started at the same speed as the car ahead (accelerative pass) and when the following car had an initial speed advantage (flying pass). A distinction is also made between voluntary (unhurried) returns to lane, and those where the overtaking car was forced to return by the oncoming car.

The first psychological study of overtaking and passing was made by Crawford (1), who regarded overtaking and passing judgments as psychophysical. He carried out controlled experiments in which measurements were made of accepted gap distance, overtaking, and safety distances. He also made a validating highway study in which observations were made of overtaking vehicles from the window of a light van. Crawford's findings on overtaking performance and safety distance will be discussed under the section on results

Silver and Bloom (8) showed that the driver could not make accurate judgments. They instructed the driver to indicate when an oncoming car was just 12 sec away, simulating a 12-sec passing time, β. Without specific knowledge of the speed of the oncoming car, drivers gave their passing judgments at the same distance. When drivers were told the speed of the oncoming car, they gave improved estimates of the passing distance associated with the 12-sec gap. Rockwell and Snider have recently shown that the driver does make a limited use of oncoming car speed in making α estimates (7). The present study may be considered the converse of the Silver and Bloom study; α characteristics are here simplified and standardized to test drivers' abilities to estimate β.

The need to consider the α and β characteristics of the overtaking decision is illustrated in a study by Jones and Heimstra (3). Drivers were told to indicate the last moment they could safely pass a lead car and avoid hitting an oncoming car. They indicated the time, but did not actually pass. The lead car speed was 60 mph. Of 190 judgments made during the study, 88 were shown to be unsafe; that is, the actual maneuver required more time than drivers gave it. The time required for the maneuver was determined in preliminary passing trials, with no opposing vehicle. Overtaking was found to be unsafe, but the study does not tell us whether drivers' errors are due to inability to assess the gap, α, or to failure in estimating vehicular passing capability, β, or to both difficulties.

THE STUDY

This research is concerned with how well drivers can judge the distance required to overtake and pass. The decision is simplified by terminating the maneuver at a fixed point on the road rather than by the passing of an oncoming car. In this way, errors in assessing the situation (α errors) are minimized. Estimations were made by drivers in their own cars, and in another phase of the research, in a government vehicle. A comparison of these conditions indicates the effects of driving an unfamiliar vehicle, as well as individual differences in performance.

The Experimental Track

The studies were carried out on the runway of the Beltsville airport (see Fig. 1). A 12-ft length of 2-in. reflectorized tape was placed across the driver's path, 1500 ft from the start of the runway, and another strip was laid down 1000 ft farther. The strips indicated to the driver the starting and the terminal position of the estimation trials.

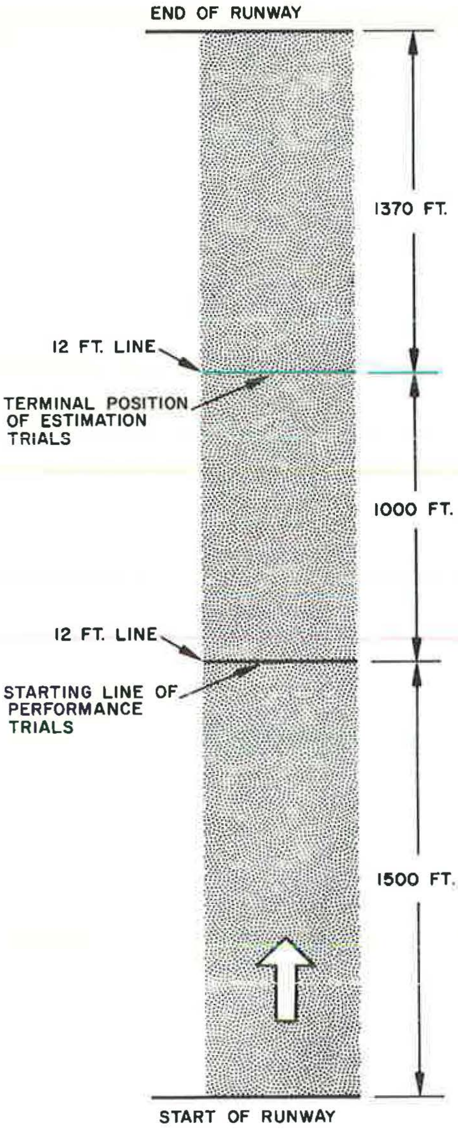

Figure 1. The experimental track.

Each strip was made more conspicuous by placing a 12 by 14-in. white box at its left margin. A numbered scale was laid out on the right edge of the runway.

Vehicles

In the first phase drivers used an unfamiliar 1965 government 6-cylinder, 145-hp Plymouth sedan. In the second phase of the study, drivers used their own cars. No attempt was made to influence selection of the vehicles. All cars completed the tests except a 1959 Volkswagen that could not overtake and pass at 50 mph in the limited runway length.

The Marking Pistol

Positions on the runway where overtaking and passing occured, were indicated by a marking pistol (American Automobile Association detonator) attached to each car's rear bumper. When the driver pressed a button, a solenoid release mechnism fired a shell containing yellow chalk at the runway. In a few instances, the subject's vehicle did not have a 12-volt battery required to activitate the solenoid. In these cases, the experimenter dropped a cloth marker to indicate position.

The Drivers

The 20 drivers who served as experimental subjects were hired from neighboring university and government employment offices. Drivers in the first phase included four males and seven females; ages ranged from 20 to 52 years, with a median of 23 years; driving experience was from 3 to 35 years, with a median of 7 years. Those in the second phase included eight males and two females; ages ranged from $18\frac{1}{2}$ to 46 years, with a median age of $20\frac{1}{2}$ years. Driving experience ranged from $2\frac{1}{2}$ to 26 years, with a median of $4\frac{1}{4}$ years. Drivers served 4 hours and were paid $2.00 an hour for their work.

METHOD AND PROCEDURE

The overtaking and passing observations were part of a series of tests which also included braking and U-turns. The overtaking and passing procedure was as follows:

Preliminary Practice

Drivers drove to the end of the runway and back twice, to familiarize themselves with the government vehicle. (Familiarization was eliminated in the second phase where drivers used their own cars.)

Overtaking and Passing Estimations

Drivers followed the test car at a distance of 55 ft. They were instructed as follows: "You will follow the car ahead and think of passing it. When you come to the closest point to the line where you can still pass, using maximum acceleration of the car, indicate the spot by pushing the button." The distance between lead and subject cars was maintained by the experimenter's instructions to slow down or speed up. The experimenter aligned a taped spot on the windshield with the hood and rear bumber of the lead car to maintain the 55-ft distance. The speeds of 18, 30, and 50 mph were controlled by the driver of the lead vehicle. An experimenter stationed on the runway recorded the data. After each observation, the marking pistol was reloaded, and the lead and experimental cars were driven to the starting point for the beginning of the next run.

Overtaking and Passing Performance

Performance trials were made after completion of the estimations. The driver followed the lead car at the scheduled pace. Instructions were as follows: "Follow the car ahead at the distance I tell you. When you get to the line, overtake and pass the car ahead, as fast as you can, and come back into the lane. Be sure you swing back into the lane." When the car was fully back in the lane the experimenter in the test car pushed the pistol button. The experimenter on the runway then recorded the position of the chalk mark.

The scheduling of the experiment is outlined in Table 1. Estimation trials followed each other without interruption, as did the performance trials. The entire work was completed in a half-day, after which the driver was paid and dismissed.

TABLE 1

SCHEDULE OF OVERTAKING AND PASSING EXPERIMENT

Series 1 (practice)	Series 2	Series 3
Estimations Trials (following U-turn and braking estimates)		
18 mph	18 mph	18 mph
30 mph	30 mph	30 mph
50 mph	50 mph	50 mph
Performance Trials (following braking performance)		
18 mph	18 mph	18 mph
30 mph	30 mph	30 mph
50 mph	50 mph	50 mph

RESULTS

Performance (β)

Performance results are given in Table 2. Standard deviations are maximum likelihood estimates. The variable error in the table is the mean deviation from the average of the two performances by each driver at each speed. Matson and Forbes, Prisk, and Crawford data are presented for comparison in Figure 2. Each government and own-car point in Figure 2 represents the average of 20 observations. The zero point of 106 ft is the minimum distance required to pass a vehicle parked 55 ft in front of the starting line.

TABLE 2

OVERTAKING AND PASSING PERFORMANCE

Car	18 mph			30 mph			50 mph		
	Mean	S.D.	S.D./M	Mean	S.D.	S.D./M	Mean	S.D.	S.D./M
(a) Overtaking and Passing Performance (ft)									
Government	385.9	53.7	0.139	606.1	77.9	0.129	1023.5	192.8	0.188
Own	440.3	76.7	0.174	628.5	121.3	0.193	1110.8	289.2	0.260
(b) Variable Error (ft)									
Government	12.3	9.8		27.0	15.4		47.3	50.8	
Own	22.0	20.2		32.7	19.9		41.7	34.6	
(c) Variable Error as Percent of Performance									
Government		3.19			4.45			4.62	
Own		5.00			5.19			3.76	

Note: Sign of the error, plus or minus, has been disregarded.

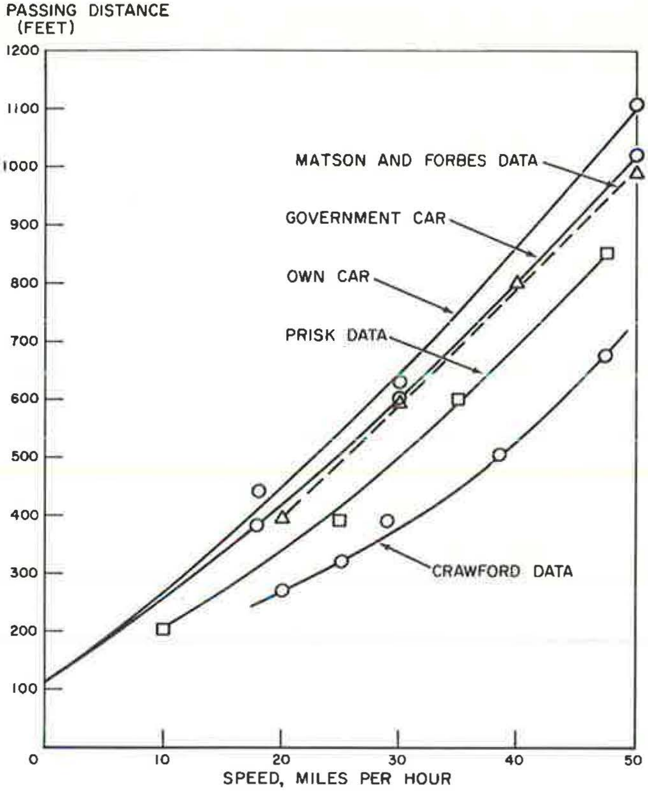

Figure 2. Overtaking and passing distances for various studies.

The performance curves indicate that as speed increased, passing distance also increased, but at an increasing rate. The least-squares fit to the own-car data is

$$D = 112.2 + 15.2\ V + 0.093\ V^2$$

where D is overtaking distance in feet and V is velocity in mph.

The performance on the government car did not differ significantly from that of drivers using their own vehicles. The Matson and Forbes data points fall close to the government car curve, and the Prisk data have the same general form, but distances are about a hundred feet less. Matson and Forbes and Prisk defined passing distance as car travel in the left lane, which is shorter than passing distance as defined here, i. e., from initial driver reaction to return to lane. Crawford's curves show still shorter distances, perhaps explained by his use of trained drivers and by other procedural differences. A complete analysis of these performance curves would take into consideration vehicular accelerations at various speeds, the driver's willingness to use accelerative capacity of the car, and the driver's varying requirements for safety distance.

Drivers differed in their ability to pass, as indicated by the distributions plotted in Figures 3 and 4. (See also standard deviations in Table 2.) These differences are evident even when drivers used the same government car: at 18 mph, driver AR overtook in 284 ft, but driver GR required 455 ft. At 30 and 50 mph variability was larger than at 18 mph. Some causes of these individual differences have already been indicated. Drivers differed in reaction time, in willingness to use maximum acceleration of the vehicle, in safety distance requirements, and they followed different paths in returning to lane at the end of the maneuver.

The vehicle driven had more effect on passing distance than the driver who performed the maneuver. Variance in the own-car condition was significantly larger than in the

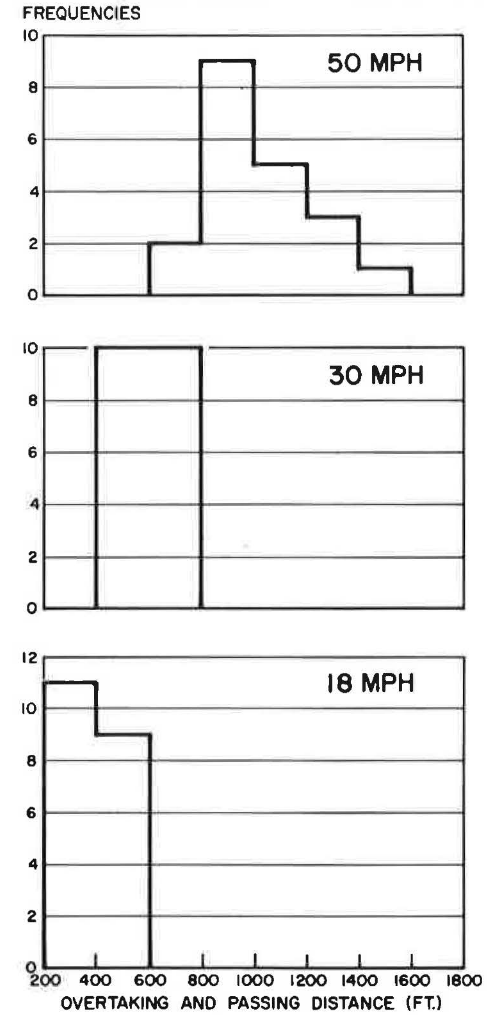

Figure 3. Overtaking and passing distances using government car.

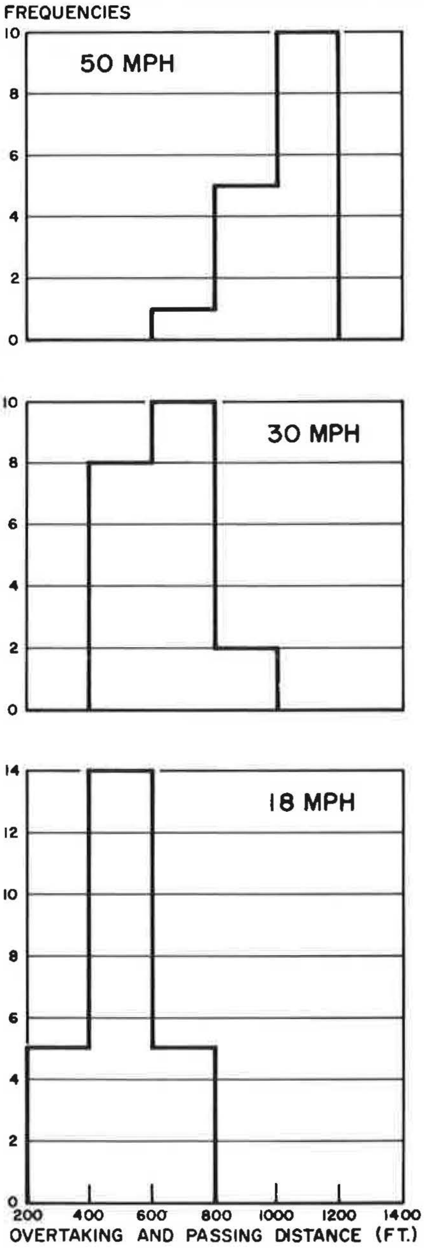

Figure 4. Overtaking and passing distances using own car.

government-car phase where the same automobile was used (F test, .05 level, all speeds). Residual variance of own car minus government car is larger than government-car variance at all speeds. These variance calculations involve the squared standard deviations of Table 2a. The importance of vehicular effects may also be seen in the individual records. The difference in performance between the highest powered car, driven by a 46-year-old woman, and the lowest powered car, driven by a 19-year-old boy, was larger than any set of driver differences on the same (government) vehicle. These vehicular and individual differences relate to the groups studied and do not necessarily apply to the universe of cars and drivers on the road.

TABLE 3

OVERTAKING AND PASSING ESTIMATION ERRORS

Car	18 mph		30 mph		50 mph	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
(a) Constant Error (ft)						
Government	197.2	179.5	312.2	205.5	317.9	208.7
Own	136.9	111.9	129.6	120.5	237.5	176.1
(b) Variable Error (ft)						
Government	42.5	30.5	52.7	40.1	29.9	14.4
Own	40.8	33.4	63.6	41.8	50.9	44.7
(c) Constant Error/Variable Error						
Government	4.63		5.92		10.63	
Own	3.36		2.04		4.67	
(d) Constant Error/Overtaking Performance						
Government	0.511		0.515		0.311	
Own	0.309		0.206		0.214	
(e) Underestimation Errors						
	N	%	N	%	N	%
Government	4	20	7	35	12	60
Own	2	10	7	35	14	78
Crawford data (interpolated)		7		39		76

Note: Sign of the error, plus or minus, has been disregarded.

Drivers' Errors

The errors made by drivers are analyzed in Table 3. Constant error listed for each speed is the difference between each estimate and the mean of the two performances by the driver at that speed, averaged over all drivers. Variable error is the deviation of each driver's constant error from his mean constant error, averaged over all drivers. The underestimation errors listed in Table 3e occur when the constant error is negative. Frequency distributions of errors made in the government and own car are plotted in Figures 5 and 6. Each chart includes the 20 errors made at a particular speed.

It may be seen from Table 3a and Figures 5 and 6 that drivers are not able to estimate passing distance accurately. Constant error varies from about one-fifth to one-half of actual overtaking distance (Table 3d). Constant error exceeds variable error at all speeds at the .01 significance level. It appears that drivers estimate their overtaking performance consistently, but in an erroneous manner.

Drivers predict their overtaking performance better in their own cars than in an unfamiliar vehicle (Table 3a). Errors in own car are significantly less (p = .05) than in the unfamiliar car (4 Fisher combination of experiments statistic). This implies that estimating vehicular performance (β') may be a learned aspect of driving skill. The finding also suggests that the driver's ability to estimate braking, U-turns, parking, and car-following requirements may furnish a useful measure of his skill and effectiveness. Little is known concerning the nature of driving skills.

Negative errors of estimate involving underestimation of maneuver distance are dangerous. Negative errors occur at all speeds, but are particularly frequent at high speeds (Table 3e and Figs. 5 and 6). At 50 mph, 60 percent of government-car estimates and 78 percent of those in own car would have been dangerous in the operational situation. The finding that underestimation is most frequent at high speeds where accidents are most serious is in close agreement with Crawford's results (Table 3e, or 1, Fig. 9).

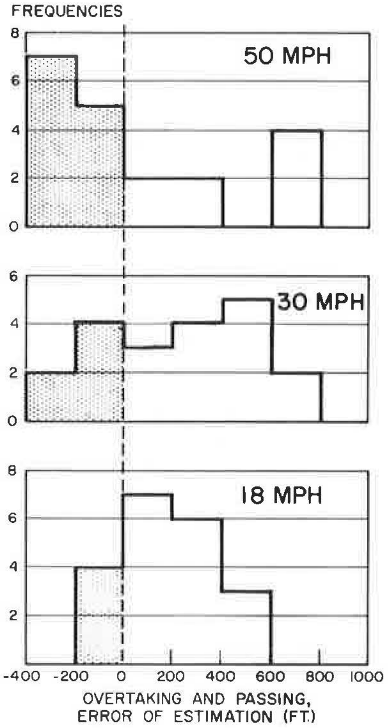

Figure 5. Estimation errors in overtaking and passing using government car.

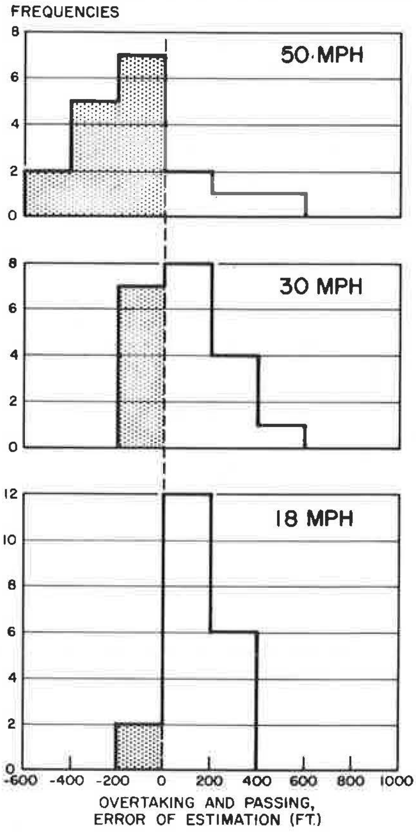

Figure 6. Estimation errors in overtaking and passing using own car.

Driver's errors and underestimations in overtaking and passing may perhaps be explained by the difficulty of the judgment. Overtaking distance varies with speed. There are as many overtaking distances as vehicular speeds. The driver cannot perform by simply learning a fixed distance, as might be the case in U-turns, or parking. The underlying speeds, accelerations, and distances are themselves subject to estimation error. For example, at 50 mph, overtaking requires about a thousand feet. An opposing vehicle, coming toward the driver at the same speed, would be twice as far away when the decision was made. The driver cannot be expected to make precise spatial judgments at such large distances.

The precise cause of underestimations at high speeds is not known. One explanation might be that the driver is not fully aware of how performance requirements (β) increase with speeds, and he may continue to act as he did at slower speeds. Whatever its cause, high speed underestimation remains a pertinent fact that highway engineers must contend with in dealing with the overtaking and passing maneuver.

Nonetheless, overtaking and passing accidents are not very frequent since several safety factors are inherent in the situation. The driver may avoid danger by not passing at high speeds, and he may insist on an adequate safety distance. If a wrong decision is made, he may drop back into lane, and the overtaken and oncoming cars may slow down and move to the shoulder. Traffic controls such as passing zones and signs also aid the driver.

APPLICATIONS

The finding that the driver is unable to estimate accurately his overtaking and passing requirements and that underestimations are frequent at high speeds implies that the maneuver requires guidance. Possible aids to the driver include the following:

1. Passing areas, and "no passing" signs (traditional aids to overtaking and passing).
2. Speed limits and other speed regulations particularly in passing zones.
3. Driver education not to pass at high speeds and to cooperate with the overtaking driver.
4. Road design modification, such as wide shoulders and addition of lanes.
5. Traffic planning to minimize use of two-lane rural roads.
6. Electronic devices informing the driver when it is safe to pass.

(Such devices are currently under development in the Traffic Systems Division, U.S. Bureau of Public Roads.)

The $\alpha\beta$ concept provides a theoretical framework that may be useful in studying driver decisions in intersection and merging gap acceptance, and in such maneuvers as U-turns, braking, parking, and car following. The $\beta'\beta$ comparison may be useful as a measure of driving effectiveness in studying learning and driving performance.

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Behavior of Drivers Performing a Flying Pass

EUGENE FARBER and CARL A. SILVER, The Franklin Institute Research Laboratories

•WHEN a vehicle traveling at a given rate encounters a slower moving vehicle, the overtaking driver must decide whether to pass the lead car (LC) or decrease his speed and follow. If no oncoming car (OC) is involved the passing opportunity is limited by the available sight distance and/or local passing zone boundaries. In this case, the correct pass/no-pass decision is a function of the speed of the LC, the overtaking rate of the passing car (PC), and the distance between each of the two cars and the end of the passing zone. The objective acceptability of a passing opportunity depends on whether or not the speeds and distances are such that the PC can complete the pass before the end of the passing zone. The following formula is a convenient way of expressing the relationship of these variables to the validity of the passing decision:

$$\text{Time Difference (TD)} = \frac{\text{DLC}}{\text{LCS}} - \frac{\text{DPC}}{\text{PCS}} - \text{SM}$$

where DLC and DPC are distances and LCS and PCS are speeds from the end of the passing zone of the PC and LC at the time of the encounter, and SM is an arbitrary safety margin left up to the driver. A positive TD predicts that the PC can reach the end of the passing zone ahead of the LC with some safety margin, whereas a negative TD indicates that the passing zone will end before the pass can be safely completed. Obviously this expression is a simplification based on the speed and distance conditions at the time of the passing decision assuming that the starting speeds will be maintained. Clearly, the passing driver may elect to increase or decrease velocity during a pass. However, the maximum acceleration and hence the minimum passing time of which a given vehicle is capable is relatively constant at highway speeds, and the TD can thus be considered as an objective measure of the acceptability of a passing opportunity.

Ideally then, in order to make valid passing decisions—that is, to pass when it is safe to do so and not to pass when it is unsafe—the PC driver would have to consider all of the relevant speed and distance cues and make a decision based on a formula similar in principle to that given. One way of expressing driver decision-making in such passing situations is to plot percent passes as a function of the TD (Fig. 1). If a driver were able to make perfect judgments of all the variables and take each of them into account appropriately he would always pass when the TD was greater than zero and never pass when the TD was less than zero, that is, he would always make a valid decision. In Figure 1, curve A represents perfect decision-making. Curve B is a more realistic prediction of passing behavior: the driver accepts some unsafe passing opportunities and rejects some safe opportunities. The slope of the curve is a measure of the accuracy with which a driver is judging and responding to the TD. The steeper the slope, the more accurate the judgment of TD. Obviously, this is a rather formidable task, involving accurate judgments of speeds and distances in complex combinations.

Considering the importance of the topic, little work has been done in the area. Normann (1) and Whedon (2) report results obtained from observations of highway passing, but data are given only for cars that did pass; thus, no information on the conditions under which drivers will or will not pass is given. The present experiment is the first known to the authors to make a systematic controlled study of passing judgment in situations where sight distance is the limiting factor.

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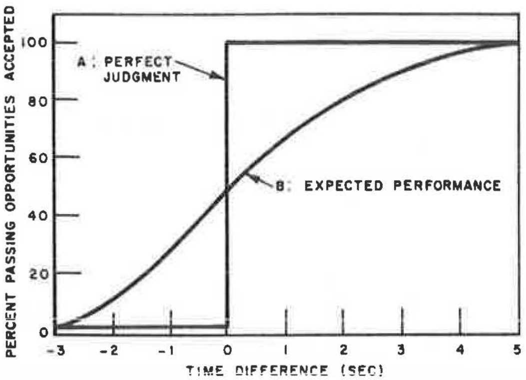

Figure 1. Ideal and expected decision-making plots.

METHOD

The experiment was conducted at the Vineland Speedway, a 1.5-mile closed-road racing circuit in Vineland, New Jersey. The course incorporates a 2600-ft tangent section that terminates in a sharp (25-35 mph) right-hand turn. The passing zone commences at a slight crest located 600 ft from the beginning of the tangent section, at which point the sight distance is 2000 ft. It terminates 200 ft from the end of the tangent section. At the end of the passing zone the sight distance into the curve is 500 ft. Both the beginning and end of the passing zone were marked by rubber cones placed at the right side of the roadway. The roadway was blacktop, 40 ft wide, with sandy shoulders. The layout of the test site is shown in Figure 2.

Two vehicles were employed in the experiment, a passing car (PC) and a lead car (LC). The PC was a 1965 Ford Galaxy sedan with a 352-cu in. V8 engine, automatic transmission, and power steering. The PC and LC were each equipped with fifth wheels to provide speed and fine distance information. Rough distance information was obtained by means of photocells mounted under the cars that sensed transverse white tape strips every 400 ft on the pavement. The PC had additional instrumentation providing continuous analog tracings of longitudinal and lateral acceleration, lateral position, yaw rate, brake pressure, throttle position, and steering-wheel position. The speed and distance data were subsequently used to determine the true positions and velocities of the test cars at various points in the passing maneuver. Throttle and steering-wheel position and brake-pressure records were used to determine at what point in a trial the subject decided whether or not to pass. The lateral-position record was used to determine at what point in the passing zone the PC regained the right lane at the completion of a pass.

The subjects in the experiment were 24 Philadelphia Yellow Cab Co. drivers, ranging in age from 26 to 58, with a minimum of 9 years of driving experience.

Procedure

Throughout a block of trials, the PC continuously circulated the track. On each lap, as the PC reached a specific point on the curve leading into the straightaway, a start signal was given to the LC, parked on the shoulder of the pavement at a preassigned point on the straightaway. On the start signal the LC pulled onto the straightaway in front of the PC and accelerated to a constant preassigned velocity. The PC driver was

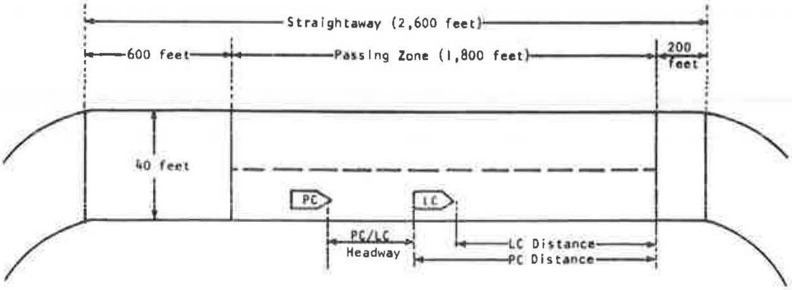

Figure 2. Vineland Speedway test site.

instructed to maintain a constant assigned speed on the straightaway until he overtook the LC, at which time he was to decide whether he could pass safely. A safe pass was defined for the subject as one that could be completed at or before the end of the passing zone (200 ft from the end of the tangent section). The subject was permitted to increase his speed during the pass if he desired. If he chose not to pass, he was to slow down and follow the LC.

TABLE 1

EXPERIMENTAL DESIGN

Speed (mph)		TD (sec)					
LC	PC	-3	-1	0	1	3	5
25	45						
35	45						
40	60						
50	60						

Experimental Design

The independent variables were (a) the speed of the PC (PCS); (b) the speed advantage or closing rate of the PC (CR); and (c) the TD as defined above, controlled by manipulating the LC starting point. Vehicle speeds and TD's are shown in Table 1. Each subject had two blocks, each block consisting of one trial at each of the 24 independent variable combinations. The primary dependent variable was whether or not the subject passed. Since desired safety margins may vary from driver to driver, no safety margin was used in computing the starting conditions required to produce the tabled TD's. A zero TD in this experiment means that the passing driver arrives at the end of the passing zone just as the right lane is regained at pass completion.

RESULTS

Data were taken from the trial records at two points: at the moment of the pass/no-pass decision and at the point of maximum PC speed on those trials in which a pass took place. The pass/no-pass decision point was determined by examining the analog records and noting when the PC began a pass, as indicated by throttle and steering-wheel position traces, or when it began to slow and follow, as indicated by the throttle position, brake pressure, and speed traces. The distance and speed data taken from the records at these points were used to compute TD's. All of the data given below were averaged across subjects.

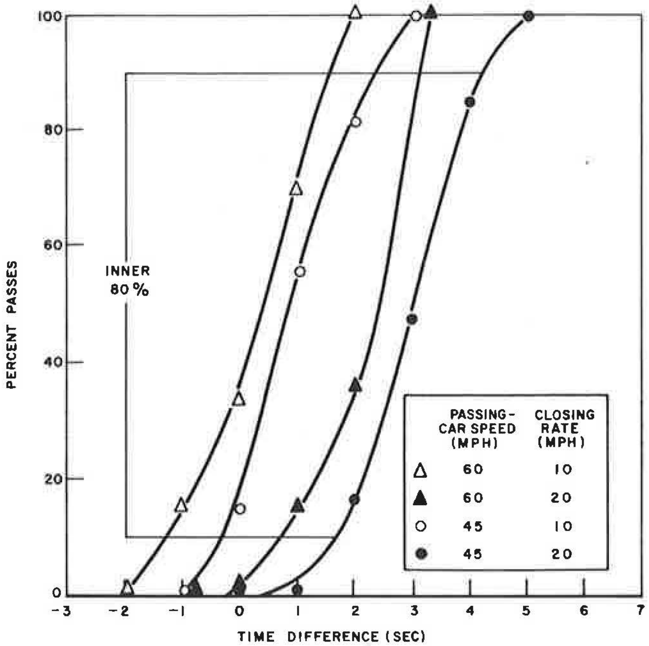

Figure 3. Percent passes as a function of TD at different PC speeds and closing rates.

Figure 3 shows percent passes as a function of the TD obtaining at the moment of the pass/no-pass decision for each of the four LC-PC speed combinations. Each curve is quite steep through the middle portion. The inner 80 percent of each curve falls within a TD range of 2.7 sec or less; within each curve very few subjects passed when the TD was more than 1.5 sec less than the threshold and very few failed to

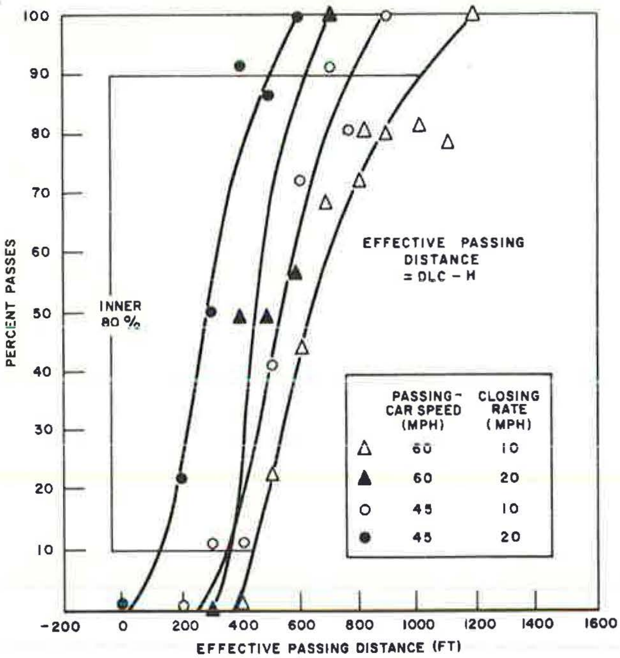

Figure 4. Percent passes as a function of EPD at different PC speeds and closing rates.

pass when the TD was over 1.5 sec more than the threshold. (The threshold TD is defined as that TD above which 50 percent of the drivers passed.) In the two 10-mph speed-advantage conditions a number of passing opportunities characterized by negative TD's were accepted. This means that, had the drivers maintained a constant speed through the pass, they would not have been able to complete the pass before the end of the passing zone. In fact, as will be seen later, most drivers did accelerate when they passed and very few passes were completed beyond the end of the passing zone.

Within a given OC-LC speed condition, all of the variation in the TD's presented to the subjects is associated with variations in the distances of the two vehicles from the end of the passing zone. If subjects were responding solely to TD, i.e., if they were taking PC and LC speeds accurately into account, there would have been little or no separation between the curves. However, this was not the case. The greater the CR and the less the PCS, the fewer the passes at a given TD. For example, in the PCS 45, CR 20 condition no drivers passed at a TD of zero, while in the PCS 60, CR 10 condition almost 35 percent of the drivers passed. The separation between these curves was found to be significant when the data were subjected to analysis of variance. This consistent separation of the curves indicates that at the greater speed advantage (20 mph) of the 25-45 and 40-60 conditions the drivers did not fully use their speed advantage in deciding whether or not to pass. Figure 3 also shows somewhat more conservative behavior at the lower PC speed (45) than at 60 mph at each speed advantage. This indicates that the subjects were not completely compensating for their own speed. Nevertheless, the spread of the curves is not nearly as large as would be anticipated if drivers were completely ignoring speed and speed advantage.

That drivers were taking speeds into account to a large extent is indicated in Figure 4, which shows percent passes as a function of effective passing distance (EPD), which is given by DLC - H, where H is headway, the distance between the PC and LC. This parameter is used rather than DLC or DPC as it takes the relative positions of the two vehicles into account. The figure is based on the EPD's that obtained at the moment of the passing decision. Although the points show considerably more scatter than in Figure 3, the curves show clear separations, indicating that with a high speed advantage subjects tended to pass more at shorter distances. The figure also shows that subjects responded to lower PC speeds by passing more frequently at shorter distance. Table 2 compares the empirical threshold EPD's with EPD's based on a TD of 2.0 sec, i.e., the EPD's that would have obtained had drivers always passed with a TD of 2.0 or more and never passed at TD's less than 2.0. A TD of 2 sec was chosen for this purpose because it is close to the overall threshold TD. The table shows generally good correspondence between empirical and ideal performance. If drivers had passed according to the ideal TD expression, the two sets of numbers would have perfect proportional correspondence. The correspondence is obviously not perfect; nevertheless, the table indicates that drivers were able to a large extent to judge and take into account the speed of the lead car and the overtaking rate in making the decision whether or not to pass.

TABLE 2

ACTUAL AND IDEAL THRESHOLD EPD's AT MOMENT OF PASSING DECISION FOR EACH PC-LC SPEED COMBINATION

Speed (mph)		Threshold EPD (ft)[a]	
PC	LC	Empirical	Ideal
60	50	640	650
60	40	450	350
45	35	530	500
45	25	190	175

[a] Based on a TD of 2.0 sec.

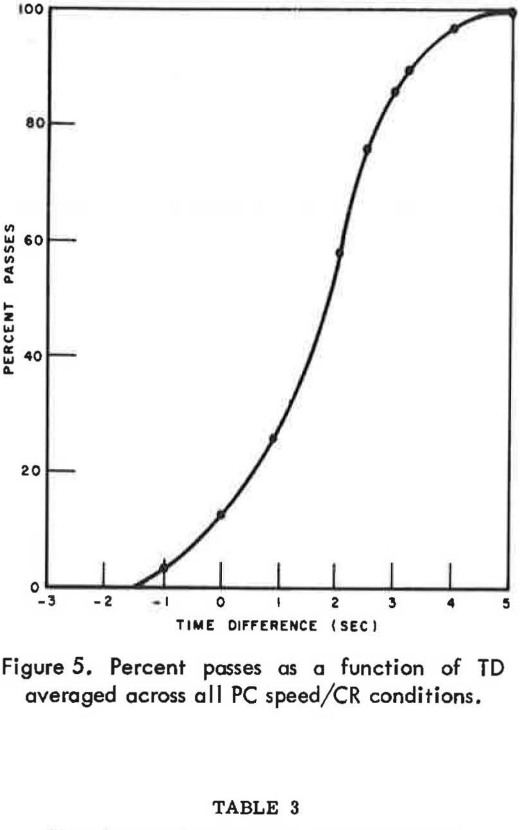

Figure 5. Percent passes as a function of TD averaged across all PC speed/CR conditions.

TABLE 3

AVERAGE CHANGE IN TD AND PCS FROM MOMENT OF PASSING DECISION TO THE POINT OF MAXIMUM PCS

Speed (mph)		ΔPCS (fps)	ΔTD (sec)
PC	LC		
60	50	12	1.8
60	40	8	1.1
45	35	14	2.2
45	25	10	1.4

The spread of each of the curves in Figure 2 reflects several sources of variability: errors in driver judgment of EPD; differences between drivers, and trial-to-trial differences in the same driver in what they judged to be an acceptable EPD; and finally, despite the fact that the curves empirically separate into PCS-CR groups, some of the variability within each curve is due to errors in judging and taking into account the PC speed and CR. Hence judgment of distance is certainly no worse than can be estimated on the basis of the variability within the EPD curves. Further, if it is assumed that distance and headway judgment per se is independent of CR and PC speed, then distance judgment was no worse than what can be estimated on the basis of the curve exhibiting the least variability. Thus in the PCS 60-CR 20 condition, all of the passes took place within an EPD range of only 400 ft, i.e., no passes took place when the EPD was less than 300 and no EPD's in excess of 700 ft were rejected. Considering the fact that several other sources of variability contributed to this spread, this suggests excellent distance judgment accurate to within ±200 ft at distances up to 2000 ft.

The subject drivers did a good job in taking all of the variables into account. Figure 5 is a plot of percent passes as a function of TD averaged across all PC speed/CR combinations. The figure shows that 80 percent of the drivers passed within only ±1.75 sec of the overall threshold TD (1.8 sec) and 95 percent passed within ±2.25 sec of the threshold.

Figure 3 shows one somewhat surprising result: the threshold TD's are generally quite low, ranging from about +0.2 to 3.0 sec. However, as noted above, the TD expression does not take acceleration into account. Table 3 gives, for subjects who passed, the average change in TD and PC speed from the moment of the passing decision to the point of maximum PC speed for each of the speed combinations. The changes in TD's are consistent with the changes in PC speed. As might be anticipated, the increases were greatest at the low PC speeds and speed advantages. Thus the TD's obtained at the moment of maximum PC speed range from 1.5 to 4.0 sec. These values should not be considered as representative threshold TD's in actual highway situations. Subjects under the experimental conditions were probably considerably less conservative than they would have been on the public roads.

CONCLUSIONS

The experiment was conducted to determine which cues a driver is sensitive to in making a pass/no-pass decision in a flying pass situation in which remaining sight distance is the limiting factor. The results indicated that drivers are responsive to all of the variables that determine the validity of the passing decision: the speed of the passing car, the passing car-lead car closing rate, the distance of the passing car from the end of the passing zone, and the passing car-lead car headway.

It was not possible to determine exactly the ability of drivers to judge distance and headway, but the results suggest that their judgment of these variables was adequate and therefore not in need of remediation. While drivers were not able to compensate perfectly for speed and closing rates, it is clear that they did respond appropriately to these variables by passing more at shorter distances when passing-car speed was low and closing rate was high. Further, drivers were able to compensate partially for errors of judgment by increasing their speed and passing in less time when a marginal (low TD) passing opportunity was accepted. The data suggest that there would be little to gain by reducing the variability associated with distance and headway judgment. Further, the passing car speed information already available to drivers from the speedometer probably cannot be improved. The only remaining critical variable that could be considered for remediation is closing rate. Despite the fact that drivers responded appropriately to CR, their accuracy in judging and compensating for CR was not known from this experiment; this problem is addressed in more detail in another experiment that is concerned with judgment of closing rate in overtaking situations (3).

ADKNOWLEDGMENT

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Driver Judgment in Overtaking Situations

CARL A. SILVER and EUGENE FARBER,
The Franklin Institute Research Laboratories

•THIS experiment is concerned with driver judgment in overtaking, the prepass portion of a flying-pass situation. The objectives are to evaluate driver judgment of time headway in overtaking and to establish the roles played by judgment of headway distance and closing rate in making the overall time-headway judgment.

Headway distance (H) is defined as the distance between the front of the overtaking car (OC) and the rear of the lead car (LC). The closing rate (CR) is the speed advantage of the OC over the LC; and the time headway (TH) is H/CR—the time separation between the OC and LC.

When one vehicle overtakes another on a two-lane highway, the driver of the OC must decide whether to pass the LC or to slow down and follow. Whether the passing situation is limited by oncoming traffic or by sight-distance restrictions, the overtaking driver must take into account H to and CR with the LC in order to make a valid passing decision. In situations where a pass is not possible, the CR will determine the minimum H at which a driver must start braking if he is to match speeds smoothly with the LC at a reasonable following distance—the greater the CR, the greater the headway at which the driver must begin braking. Ideally, then, decision-making in an overtaking situation should be based on the time headway (TH) between the OC and LC at the time of the decision.

The prevalence of rear-end collisions on two-lane highways suggests that drivers are very poor judges of TH. Results of a previous study (1) indicated that drivers are sensitive to the closing rate with a lead vehicle in an overtaking situation but are prone to over- or underestimate time headway when closing rates are high or low. Experiments performed by Michaels (2) indicate that at CR's over 10 mph, the CR cue provided by the rate of change of the visual angle subtended by the LC is well above threshold at distance headways equivalent to TH's of 5 to 10 sec. That drivers can detect CR's in these situations does not mean, however, that they can usefully discriminate one CR from another. Further, even if drivers can judge CR with reasonable accuracy, there remains the problem of taking this information into account usefully to estimate the TH.

The purpose of the present study, therefore, is to evaluate the ability of drivers to judge headway and closing rate in overtaking situations.

METHOD

The study was conducted on a completed but unopened section of I-95 in Philadelphia. Experimental runs were performed on one side of the roadway, which consisted of four adjacent 12-ft lanes. The test section was several miles long and incorporated a 3500-ft level tangent section on which test runs were performed.

Two cars were used in the tests: a Rambler station wagon (LC), and a Chevrolet Impala sedan (OC). The OC was equipped with a 327-cu in.-V8 engine (250 hp), power steering, automatic transmission, and standard brakes.

Ten Philadelphia public school teachers with a minimum of 8 years of driving experience were used as subjects.

Procedure

At the start of each trial the driver of the LC accelerated to the assigned speed for that trial on the right-center lane of the roadway, and maintained that speed constantly

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OCS = OVERTAKING CAR SPEED (MPH); CR = CLOSING RATE (MPH)

TYPE OF CLOSING RATE	5-SECOND TIME HEADWAY						10-SECOND TIME HEADWAY					
	OCS = 45			OCS = 60			OCS = 45			OCS = 60		
	CR=10	CR=20	CR=30	CR=10	CR=20	CR=30	CR=10	CR=20	CR=30	CR=10	CR=20	CR=30
VARIABLE (PRESENTED IN RANDOM ORDER)												
CONSTANT (CONSTANT FOR 12 TRIALS)												

Figure 1. Experimental design.

throughout the trial. A few seconds later the OC, driven by the subject, accelerated to its assigned speed for that trial, following the LC in the same lane. The assigned OC speed was always higher by 10, 20, or 30 mph than the LC speed, so that on every trial it eventually overtook the LC somewhere on the roadway. The starting positions of both the LC and OC and the delay of the start of the OC were varied randomly so that the point on the roadway at which overtaking took place varied randomly from trial to trial. The subject driver was instructed to maintain the assigned speed as accurately as possible throughout the trial. When the subject judged that the TH between the OC and LC was equal to a given number of seconds, he was to indicate this verbally, pull into the left-hand lane while maintaining his assigned speed, and continue until he had passed the LC. On some trials the subject was to indicate a 5-sec TH, and on other trials, a 10-sec TH. The experimenter, riding with the subject in the OC, used a stopwatch to measure the actual TH. At the end of each trial, the subject was told what the TH actually was when he gave his estimation. The accuracy with which a subject could judge the TH was clearly dependent on his ability to judge both distance to H and CR with the LC.

Experimental Design

Each subject had four blocks of 36 trials. Each block consisted of 6 replications of each of 6 OC-LC speed combinations. The various speed combinations produced 10-, 20-, and 30-mph CR's and, in a block of trials, each subject experienced each CR 6 times at an OC speed of 45 mph and 6 times at a speed of 60 mph. In two of the blocks (variable-CR blocks), the speed combinations were presented in random order. The other two blocks were constant-CR blocks, which were divided into three sub-blocks of 12 consecutive trials at a constant CR. For expample, a typical constant-CR block started with 12 trials at a 20-mph CR, followed by 12 trials at a 10-mph CR, followed by 12 trials with a 30-mph CR. Subjects had no break between sub-blocks. Within a sub-block, the order of presentation of OC speed (and hence LC speed) was random. Prior to the start of each sub-block in constant-CR blocks, the subject was told the CR for the next 12 trials and was reminded of the CR prior to the start of each trial. On the variable-CR blocks, subjects were given no knowledge of the CR beyond their own judgment of it. On one each of the constant-CR and the variable-CR blocks, the subject was asked to estimate when he was 5 sec behind the LC, and on the other two blocks he was asked to indicate when he was 10 sec behind the LC. The experimental design is shown in Figure 1.

On a variable CR-block, the accuracy with which a subject could judge a 5- or 10-sec time gap was clearly dependent on his ability to judge the distance to the LC, and the CR with the LC. However, on constant-CR blocks, the relationship between H and TH was constant, so that subjects had to judge only the H in order to estimate the TH.

RESULTS

Table 1 shows the variances of the estimated TH's computed across subjects and CR as a function of the variable-CR and constant-CR trials and of the TH to be judged. The

TABLE 1

VARIANCE OF TH ESTIMATES FOR CONSTANT AND VARIABLE CR's AS A FUNCTION OF OC SPEED AND TH TO BE JUDGED

OC Speed (mph)	TH Estimates (sec)			
	Constant CR		Variable CR	
	5	10	5	10
45	1.13	2.64	1.68	8.09
60	1.10	1.19	1.71	6.30

TABLE 2

VARIANCE OF TH ESTIMATES WITH CELL VARIANCES OF SCORES EXPRESSED AS PERCENT DEVIATIONS FROM CELL MEANS

OC Speed (mph)	TH Estimates (sec)			
	Constant CR		Variable CR	
	5	10	5	10
45	1.76	1.29	2.62	4.29
60	1.72	1.85	2.17	3.28

effect of OC speed was not significant; however, the variances associated with the variable-CR condition were consistently and significantly (<0.01) larger than the constant-CR variances.

The size of the TH to be judged also had a significant (<0.01) effect on the variances; the variances of the TH judgments around 10 sec were considerably larger than the variances around the 5-sec gap. The variances under the variable-CR, 10-sec TH condition are especially high.

The findings indicate that under constant CR, subjects were able to judge TH more accurately than under the variable-CR condition. The significantly larger variable error associated with the variable-CR condition can be attributed to the necessity of subjects having to judge and take into account the CR as well as distance in estimating the time gap. However, the variances associated with the 10-sec time gap are spuriously inflated because the absolute value of deviation from the mean of a given percentage would be twice as large with a 10-sec mean score than with a 5-sec mean score. For example, a 20 percent error in judgment would mean an error of 1 sec in estimating the 5-sec gap, but 2 sec in estimating the 10-sec gap. The data of Table 1 are given in Table 2 with each variance computed on scores expressed as percent deviation from the cell means. Figure 2 shows these data in graphic form.

With the variances so computed it is seen that the size of the TH has no effect on variable errors expressed as a proportion when the CR is constant. Under the variable-CR condition, the variance increased with TH and was significant at an OC speed of 45 mph, suggesting that subjects found it more difficult to judge CR at the greater headway distances associated with the 10-sec condition.

Under the constant-CR condition, subjects had to judge only distance (H) to make an estimate of the TH; hence the variability of the TH estimates is directly related to distance-judgment ability. Table 3 gives for the constant-CR trials the standard deviations of the time headways judged equal to 5 or 10 sec, the 95 percent confidence limits expressed as a percentage of the TH, and the same confidence limits expressed in feet. The confidence limits tend to decrease, indicating an increase in judgment accuracy with increasing closing rate. This effect is statistically significant (<0.05), suggesting that subjects were able to judge larger distances with better proportional accuracy than smaller distances. The confidence limits associated with judgment of the 10-sec gap are less than those associated with the 5-sec gap, but this difference is not significant.

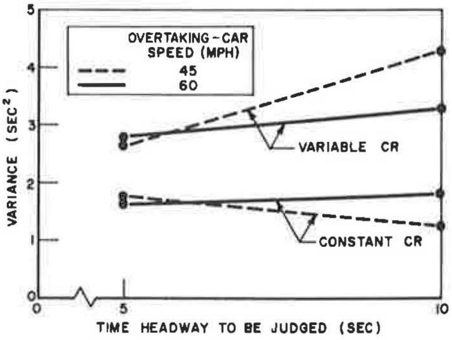

Figure 2. Variances of TH estimation error scores expressed as deviations from cell means as a function of TH to be judged.

Table 4 gives, under various combinations of conditions, the mean of the TH's that actually obtained when the subjects judged themselves to be 5 or 10 sec away from the LC. Since OC speed had no effect on the mean data, it is not included as a variable. For both constant-CR

TABLE 3

DISTANCE JUDGMENT CONFIDENCE LIMITS FOR DIFFERENT CR's AND TH's CONSTANT-CR TRIALS

TH Judgments (sec)	CR (mph)	Equivalent Distance (ft)	Standard Deviation of TH Judgments (sec)	95 Percent Confidence Limits	
				± %	± Distance (ft)
5	10	73	1.04	34	25
	20	147	0.58	19	28
	30	220	0.32	11	23
10	10	147	1.20	20	29
	20	293	0.57	9	28
	30	440	0.44	7	32

TABLE 4

MEAN TH ESTIMATES AS A FUNCTION OF CR FOR CONSTANT AND VARIABLE CR's AND TH JUDGMENTS

CR	TH (sec)	CR (mph)		
		10	20	30
Constant	5	5.52	5.12	4.68
	10	10.37	8.95	8.96
Variable	5	6.26	5.10	5.83
	10	11.02	8.92	7.77

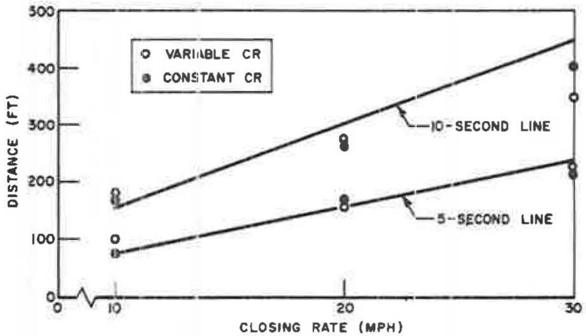

Figure 3. Mean distance judged to be equivalent to a TH of 5 or 10 sec as a function of CR.

TABLE 5

MEAN TH ESTIMATION ERRORS EXPRESSED AS PERCENTS

CR	TH (sec)	CR (mph)		
		10	20	30
Constant	5	10.4	2.0	- 6.4
	10	3.7	-10.5	-10.4
Variable	5	25.0	2.0	16.6
	10	10.2	-10.8	-22.3

and variable-CR conditions, the TH's tend to decrease with increasing CR. This effect is statistically significant (<0.05).

Table 5 presents the data of Table 4 with each entry expressed as a percentage error. Under both the 5- and 10-sec conditions, the proportional errors are higher under the variable-CR condition than under the constant-CR condition, but this effect is not significant. A stronger effect was produced by the size of the gap to be judged. At the higher CR's the proportional error of TH judgments was significantly smaller under the 5-sec condition than under the 10-sec condition.

These effects are illustrated in Figure 3, in which the distances judged by subjects to be the equivalent of 5 or 10 sec are plotted as a function of constant and variable CR. The two lines represent the distances associated with a 5- and 10-sec TH at each CR. Deviations of points from the line represent a bias error in estimating the TH. Note that, in general, the bias errors about the 5-sec TH are low, and the performance under constant-CR and variable-CR conditions is similar. Under the 10-sec condition, however, subjects tended to overestimate the TH increasingly as CR increased. This effect is more pronounced for the variable-CR trials than for the constant-CR trials. The three-way interaction between TH, CR, and variability vs constancy of CR is significant (<0.01). That is, under the 10-sec TH condition, errors of the TH estimation increased with CR, but increased more under the variable-CR condition.

CONCLUSIONS

The only condition that had a significant effect on the variability of judgments was constancy/variability of CR. The variable-CR produced a larger variable error in judgment than did the constant-CR condition. In general, the variability was about twice as high when CR's were randomly varied than when CR's were constant. The increase in variability under the variable-CR condition is attributed to the subjects' need to judge and take into account CR under that condition.

Headway-distance judgment accuracy was good: subjects estimated H's to within about 30 ft, independent of the distance, 95 percent of the time. The proportional error decreased with the distance to be judged and at 440 ft 95 percent of the judgments were within 7 percent of the true H. Under the 5-sec gap condition, the variability/constancy of CR's had little effect on constant errors of judgment of the TH. However, in estimating 10-sec TH's under the 30-mph CR condition, subjects under the variable-CR condition overestimated the TH to a significantly greater degree than they did under the constant-CR condition. Apparently, under the variable-CR condition, subjects tended to underestimate the 30-mph CR.

If subjects had been completely unable to estimate and take into account CR, and had based their estimate of the TH solely on H, the variable-CR mean would have produced a horizontal line in Figure 2. The fact that the H's increased with CR under the variable-CR condition indicates that subjects were sensitive to CR (3). This result contradicts the findings of the passing experiments (2) in which subjects were completely insensitive to the CR with an oncoming car at distances over 1200 ft. However, as stated above, TH estimates varied significantly more when subjects had to judge the CR. The fact that subjects were able to judge CR to a limited degree under the controlled conditions of an experiment in which they were motivated to perform does not mean that drivers behave this way on the highway. Also, after a few trials the subjects become familiar with the range of CR's and the high (30-mph) closing rate did not surprise the subjects. Had the 30-mph CR occurred more rarely so that it was not anticipated, it is likely that the associated TH's would have been substantially overestimated.

On the highway, overtaking drivers must judge and take into account the TH with a lead car to make good decisions. Poor TH estimates can lead to errors of several kinds. All things being equal, the less the TH, the less the time required to complete a flying pass. Hence underestimation of TH can lead to the acceptance of hazardous passing opportunities; overestimation of time can lead to the rejection of safe passing opportunities. In situations where a pass is not possible, overestimation of TH can result in a rear-end collision.

Since the judgment of CR is a significant factor in errors of TH judgment, CR must be considered as a candidate for remediation. However, further experimentation in this area is required to establish the influence of providing CR information on TH-judgment accuracy. The experiment produced no results to suggest that headway-distance judgment is a problem, and no remediation in this area is indicated.

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Research Requirements for Determining Car Handling Characteristics

JOHN VERSACE and LYMAN M. FORBES, Ford Motor Company

Distinction is made between handling, which is the behavior of a car-man combination in actual driving, and other variables, such as vehicle directional response properties and vehicle component designs. The relation between car-man handling behavior and safety (as indicated by the frequency and extent of accident injuries and fatalities) is discernible in accident statistics. But the relation of the car-only portion (its directional response properties) to the frequency of accidents and consequently to the extent of injuries and fatalities is largely unknown. Furthermore, the relation of the vehicle response properties to actual handling in the driving population is poorly known, partly because of difficulties in defining handling with sufficient objectivity to allow for its measurement. The paper briefly summarizes present practice in the development of car design to a handling criterion, and presents some basic considerations for research studies that will relate handling behavior to vehicle properties. A history of the recent interest in relating handling to vehicle properties is also included.

•IF one reads the sports car magazines it may seem that a lot is known about car handling and that performance requirements for handling could be set up easily. In a sense this is true because vehicle planners do indeed specify handling requirements and vehicles are designed and developed to meet them.

However, two aspects of the matter cause difficulty. First, there is no sure transformation of what is now mainly subjective knowledge obtained through long and intimate experience into quantitative, objective, instrumental procedures for unambiguous measurement and assessment of handling quality. Second, among the many handling objectives that may be considered, safety has become a preeminent one, but the relation between handling and safety is only poorly understood.

THE VARIABLES

Distictions should be made among several classes of variables, some objective, others only vaguely conceptual and becoming more so as they approach the area of interest to us:

1. Vehicle design. This is the set of geometric and kinematic design statements that describe the structure of the vehicle and its components. Included are such things as the location, orientation, and physical properties of components such as springs, dampers, linkages, and gears. It also includes such quantities as camber, caster, roll steer, spring rates, damping coefficients, component weights, inertias, location of motion axes, and centers of gravity. Many criteria and constraints determine the particular values for these various components, such as the range of vehicle loads that will be encountered, reliability and durability, ride quality, space availability for mounting,

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conflict with other subsystems that have other objectives, and of course, cost and mass production feasibility, in addition to handling quality requirements.

2. Vehicle directional response. This group of variables views the vehicle more as a "black box" and describes the overall input-output relations for directional motion. These variables include steady-state understeer/oversteer, yaw damping, transient overshoot, resonant frequencies and response times for clamped and free inputs, and transfer or describing function characteristics. The measurements are obtained by putting the vehicle through a standard set of stylized motions that will allow for the instrumented recording of a suitable set of angular and directional velocities and accelerations. These descriptions are a rather new development, relatively speaking, and a standardized approach to them is only recently under development. The last section of this report covers the history of relating handling to vehicle response. Because the directional response of the vehicle becomes nonlinear beyond moderate motions, the directional response variates are largely contingent upon other momentary states, particularly lateral acceleration. The directional response variables have often been referred to as the handling variables, or even as "handling" itself. However, they merely describe vehicle motion when designated inputs are applied to the vehicle. Mathematical models to describe vehicle directional control have ranged from simple functional models that embrace or fit the measurable vehicle response to structural models that attempt to determine this response from the design elements.

3. Handling. The term "handling" refers to the behavior of the car-man combination in real driving situations and thus embraces a wide variety of possible maneuvers and environmental and roadway conditions. Because driving behavior depends on the presence of a self-adjusting, adaptive, learning, expecting, predicting, and decision-making component—the man—the attribution of handling characteristics to only the vehicle makes for an unbalanced approach to the problem.

The great number of possible handling maneuvers and circumstances suggests a further division into normal handling and emergency handling. Normal handling might refer to the ability to deliberately maneuver quickly, flexibly, and effectively. Emergency handling might refer more to those maneuvers and motions that tend to keep the driver out of further troubles once he has already gotten into trouble, such as having lost traction from taking a curve too fast. Normal handling involves planned actions; emergency handling involves unplanned, no-judgment, rapid actions. Vehicle characteristics may be more favorable to the one or the other.

4. Ergonomics. A number of factors that relate to the driver's ability to operate the vehicle, such as the velocity, force, power, and modulation he can apply to the steering, brake, and accelerator controls, are modified by the geometry of the driver's workspace and by his motivation. Our main interest here is in normative relations, that is, the distribution of velocity, force, and power capabilities in the population of drivers.

There has also been interest in the development of mathematical models intended to describe the human as an element of a closed-loop control system. Their main sources have been mathematical analyses of some military systems where the dynamic characteristics of an idealized human controller could be described for some rather narrowly definable tasks, such as the tracking of a target in a reticle, or aircraft instrument flying. Such driver models would be combined with the mathematical representation of the vehicle directional properties. It has been difficult both to identify the output variables that the driver in real world situations uses for feedback, and to scale or transform them into functional parameters. Just as our concern above was with the distribution of capability in the population, so we would also want to know the statistical distribution of the "driver" terms in these mathematical models. In addition, these models cannot deal very well with such factors as alertness, attentiveness, aggressiveness, cognizance, expectance, and so on. Except for a limited range of maneuvers, these models and these conceptualizations have not yet showed any strong application to the driving situation.

5. Safety. Safety, or at least unsafety, has a fairly specific meaning, being directly measurable by the number and extent of injuries and fatalities occurring as a result of accidents. The only relevance of vehicle controllability to safety is in limiting the occurrence of accidents and, therefore, the number and extent of injuries and fatalities. A number of handling characteristics, such as those often proposed by the sports driving

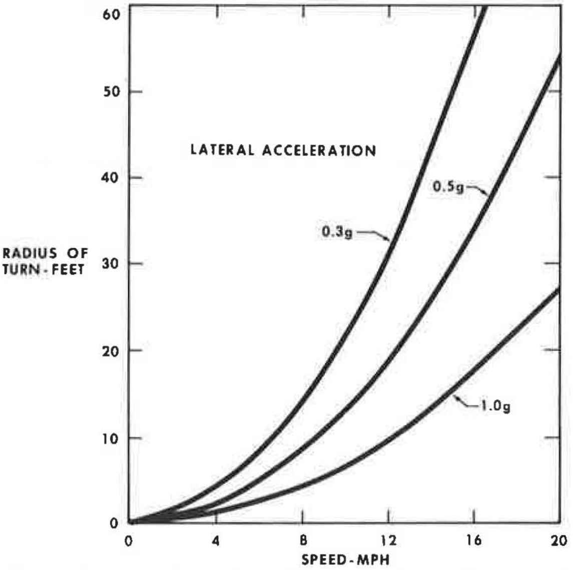

Figure 1. Lateral acceleration curves for various speeds and radii of turn.

enthusiast, may be desirable for numerous reasons, but these may or may not at the same time reduce the number of accidents. Or, they may for some persons in some situations, but they may not be appropriate for others.

Predicting Safety

We must distinguish between actual safety and presumed safety. It is difficult to demonstrate that actual safety has been achieved, according to the criterion described, because it requires a retrospective enumeration or controlled comparison of accident statistics. Because this final criterion—a count of injuries and fatalities resulting from "loss-of-control" accidents—is so difficult to estimate in advance, we look for a substitute measure that should predict it and can presumably be used in place of it; thus, presumed safety. It sometimes seems there are almost as many presumptions about handling and safety as there are people who want to talk about it. However, we may have to content ourselves with presumptuous criteria, based on common sense and other judgments, but their relevance to the final criterion should at least remain open to challenge.

It is easy to state in general terms what one would like to accomplish: it should be difficult for the driver to lose control of the vehicle. Even though that seems reasonably understandable, there is an acute problem because the goal is very subjective, lacking an unequivocal method of objective measurement. This goal recognizes the presence of the driver as an integral, if not very predictable, component in the system.

Losing control of the vehicle means that a driver has lost control. Can the vehicle's characteristics be shaped so that the car is always within the control capability of the driver? Any driver can command virtually any car to exceed its lateral road-holding capability. For example, 1 g lateral acceleration can be built up by trying to take a turn of 27-ft radius at 20 mph, as Figure 1 illustrates. We have to arrive at some convention as to what is unreasonable or unacceptable driver action before we can begin applying constraints to the vehicle.

Handling has not been satisfactorily defined in terms of the instruments or procedures needed to measure it. Instead, we have what are mainly narrative descriptions of subjectively appraised behaviors. So, an objective measure of compliance to a criterion is not readily available either.

One step removed from handling behavior itself are properties that can be measured and that the manufacturer can influence: the vehicle directional response characteristics. These dynamic properties are, in turn, the result of component designs and arrangements. However, at every step removed, relation to the final criterion of accident occurrence and hence to injuries and fatalities becomes more tenuous. There will invariably be an erosion of predictability through use of intervening or intermediate criteria. There may be temptation to use reliability and repeatability of a measurement as justification for its choice, but we can find ourselves in the position of the drunk searching for his lost keys in the illumination from the street lamp rather than where he dropped them. Of course, performance objectives can be more validly related to other more proximal criteria, but then that may not necessarily be a reduction in accidents that cause injuries and fatalities.

PRESENT PROCEDURES

How, then, is the handling quality of a car arrived at by the manufacturer? The answer is: mainly by experienced feel and a long background in meeting market requirements. The emphasis is on handling behavior as such, rather than on directional response measurements, and on repeated modification of design until prescribed characteristics are achieved. Great reliance is placed on seasoned experts who judge the adequacy of handling-like performance in as wide a variety of critical driving situations as can be repeatably undertaken. Wherever these behaviors can be reduced to objective, numerical requirements, it is done. There is an increasing reference to vehicle response measurements as guides in development, although actual driving experience still dominates. The relation to actual safety of the handling behaviors and their objective approximations is still mainly a matter of reasoned and experienced plausibility.

Present procedures within the automobile industry for developing acceptable handling and stability characteristics involve at least the following steps (Fig. 2):

1. Specifications. A set of objectives for ride, handling, and stability is established in general terms by company planning groups and vehicle engineering offices. These general objectives are transmitted to chassis design engineers and vehicle development engineers in the form of specifications and requirements.

The following statements are a small sample of typical requirements, and compliance to them is determined by an extensive evaluation program, which will be described later.

> Maximum handling shall be determined by driving the vehicle on the test track handling course in both directions to establish safe handling speeds. Handling during high-speed driving and passing shall be evaluated on the expressway and at the main test track.
>
> The steering wheel correction must not exceed ±7 deg when traveling on a straight, flat highway at speeds up to 65 mph.
>
> The steering wheel must return to within 90 deg of straight ahead position within 2 sec after wheel release from a normal cornering operation (1.5 turns of the steering wheel). Tests are conducted at constant vehicle speed of 14-16 mph on smooth, dry concrete with the steering gear at maximum preloads and suspension geometry set to nominal value.
>
> For parking maneuvers on smooth pavement with the engine operating at minimum idle speed, the steering wheel speed of 60 rpm without overtaking the hydraulic assist shall be considered minimum.

2. Initial designs. The chassis design engineers prepare the initial designs within the constraints and definitions of the total vehicle. These will depend on size, weight, and type (economy, sports, family, luxury) of the vehicle and on the full range of power plants and power options to be accommodated. Prototype parts are ordered and installed on test and development vehicles. These may be full prototype, or at least mechanical prototype in nature, and are often modifications of previous models that have the required characteristics.

3. Development. Development engineers then take this "first cut" design and modify the suspension components, the springs, shock absorbers, wheels, tires, and steering system as needed, until the handling performance of the developmental vehicle conforms to their interpretation of the requirements. During this development program, use is made of proving ground facilities and public roads. The developmental vehicle is tried in every conceivable maneuver under various types of road surface conditions, such as straight level roads for checking directional stability and wind wander, roads with moderately rough and undulating surfaces, gravel roads, proving ground handling circuits, winding hilly roads, expressway lane changing, and skid pad runs to determine vehicle response characteristics.

Passenger and cargo load conditions are varied as part of the development program. For car lines offering heavy duty or "performance" suspension options, additional criteria are often imposed, such as elapsed time to negotiate standard test track handling circuits.

Engineering test labs provide the development engineers with vehicle information such as ride rates, natural roll rates, front- and rear-end geometry curves, front and rear roll steer, steering efforts, steering compliance, and front and rear recession rates. Not all of this information is required in every case to allow for effective development.

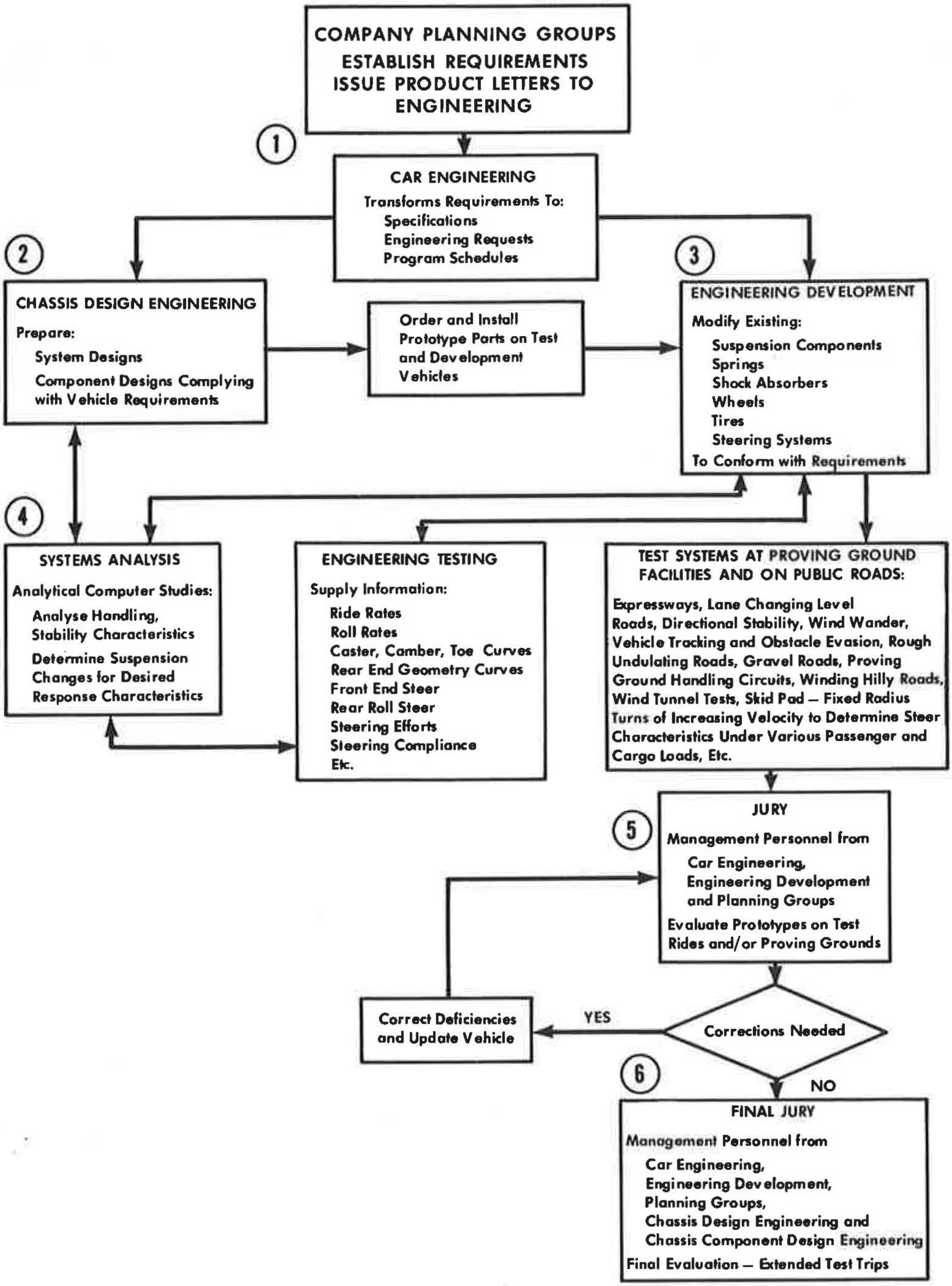

Figure 2. Procedures for developing acceptable handling and stability characteristics.

4. Analysis. There is increasing use of analytical and computer methods to predict and evaluate response and stability characteristics from initial design assumptions and to determine suspension changes that might affect them. These mathematical procedures do not embrace all the subtleties of handling, which still requires "seat of the pants" appraisal.

5. Evaluation. After development engineers have "wrung out" the design through this extensive test and modification procedure, a jury consisting of engineering and product planning management personnel further evaluates the prototype vehicles on short test trips and on proving ground facilities against the specified requirements. Great attention is paid to safety and durability. Suggested vehicle modifications again are made and further evaluations follow. Throughout all the evaluation trials, performance is measured in various ways, most of them subjective. For example, the simplest and most obvious is a narrative case history containing descriptions of the performance and the related design and response characteristics. The evaluators' judgments are further conditioned by some quantitative measures, such as the maximum speed at which particular maneuvers could be successfully carried out in standardized situations.

The various aspects of handling-like performance, such as wind wander and passing ability, and overall handling quality, are often summarized in rating scales, such as:

1. Unacceptable, production reject, would be noted by all customers; poor component performance.

2, 3. Unacceptable, production reject, would be noted by average customers; poor component performance.

4. Unacceptable, production reject, response is objectionable; complaints from average customers, specifically directed toward vehicle component.

5. Borderline acceptable, complaint from critical customers, moderate response objectionableness; borderline component performance.

6. Borderline acceptable, complaint from critical customers, little response objectionableness; component only barely acceptable.

7. Acceptable, complaint from critical customers, very little response objectionableness; component performance fair.

8. Acceptable, some critical customers still may complain, but only a trace of response objectionableness; good component performance.

9. Acceptable, only a trained observer likely to complain, no noticeably objectionable response; very good component performance.

10. Acceptable, no perceptible condition for complaint; excellent component performance.

Note that this is a scale for evaluating the acceptability of the vehicle. In this case it would be used for handling quality. But, it is not a scale that would estimate the perceived magnitude of handling performance directly and absolutely. Therefore, vehicles might differ in their overall handling quality and still achieve the same rating because the assumptions as to the expected or appropriate handling depends on the type of vehicle. Developmental models of a Mustang, a Lincoln Continental, and a light truck might each achieve the same numerical rating, but the absolute handling characteristics would not likely be the same. Because subjective judgments are involved, the ratings would have all the characteristics of ratings. That is, they will be affected by individual differences among raters; by a drift or adaptation tendency determined by the context of the tests and a counteracting regression toward the center of the scale; and by the lack of additivity and ratio properties for the scale values, which hinder attempts to combine ratings for purposes of statistical analysis. On the other hand, the long experience and intense specialization of the experts who do this work promotes confidence in the reliability and meaningfulness of the ratings. Even so, ratings have only a limited use, being used as short-hand summaries of more generalized conclusions and evaluative descriptions, mainly to expedite internal communication.

6. Acceptance. After the initial management evaluation, the full prototype vehicles then are updated to the latest configuration, and final management sign-off trips are conducted. These are very often major cross-country trips that cover a wide variety of roads and driving conditions, particularly for any significantly new model, and utilize a number of vehicles, including previous models and competitive "target" cars.

FACILITIES

Facilities requirements depend on which of the sets of variables are of greatest interest. If it is handling as such, then facilities resembling ordinary roads must be provided. These should be protected because presumably there will be a great deal of deliberately marginal driving. The environment may have to be rigged to produce the circumstances that elicit the loss of control behavior. For example, dummy targets may be arranged to pop up unexpectedly and thereby cause the driver to take evasive action. Surfaces with different frictional characteristics (including wet surfaces), curves of various radii, pavement drop-offs, bumps and holes, and varying lane crowns may have to be provided. This is the sort of thing generally found at the vehicle proving grounds. The test driver or development evaluator must be an expert, but at the same time should represent ordinary drivers in some meaningful way, and his selection may be an important part of the process. For many tests, completely innocent and naive drivers may be required.

On the other hand, if measurements of the vehicle response parameters are to be made, then a large facility for exercising the car in a wide range of speeds and paths must be provided, together with considerable instrumentation. The test driver in this case serves as an automaton, a provider of input. His function is to put the vehicle into the various pre-programmed paths and trims required to build up lateral acceleration in the successive values needed for instrumentation readings of other car responses. Ideally, a robot would be used. A large paved area is required. To allow for the safe buildup of at least 0.7 g lateral acceleration at 75 mph, in various approaches to that state, a flat uniform surface as much as 500 by 2000 ft would be required.

To relate vehicle response to component design factors, a laboratory facility will allow for measuring or calculating inertias, spring rates, damping factors, kinematic changes of geometry, and dynamic tire properties. Road surface characteristics must be measurable, such as with skid test trailers. In addition, to appraise the influence of aerodynamic design on vehicle response, batteries of wind machines and/or wind tunnel testing may also be required.

Needless to say, facilities of this sort would be very large and very expensive, and they are not yet widespread in any comprehensive form, even among the automotive manufacturers.

RESEARCH PROGRAM

The broad outlines of a prototype minimal program can be stated simply: determine the manner in which safe car-man handling performance relates to the objectively measurable vehicle control properties.

The essential feature of the experimental portion of the program is a three-phase approach requiring measurement of car-man handling performance and vehicle directional motion properties, and then their correlation:

1. Techniques for measurement of actual handling, that is, car-man driving behavior, would have to be developed. These measures would constitute a set of dependent variables.
2. Vehicle directional motion properties (understeer, response time, etc.) would constitute the set of independent variables. Selected combinations of values of these properties would then have to be built into test vehicles used for handling trials.
3. Correlation of the two types of measures taken in a series of handling trials, that is, correlation of car-man handling behavior and the vehicle motion properties, would lead to calibration of the latter into graded zones of acceptability. Handling criteria could then be based on vehicle response performance. Figure 3 summarizes the main features of an experimental program.

Dependent Variables

One of the first things that needs to be studied is the specific way that safety is supposed to be achieved through handling performance. Although some prescriptions for cures have been put forth, it is difficult to find out specifically what it is that needs to be corrected. We may even ask if there is a handling problem.

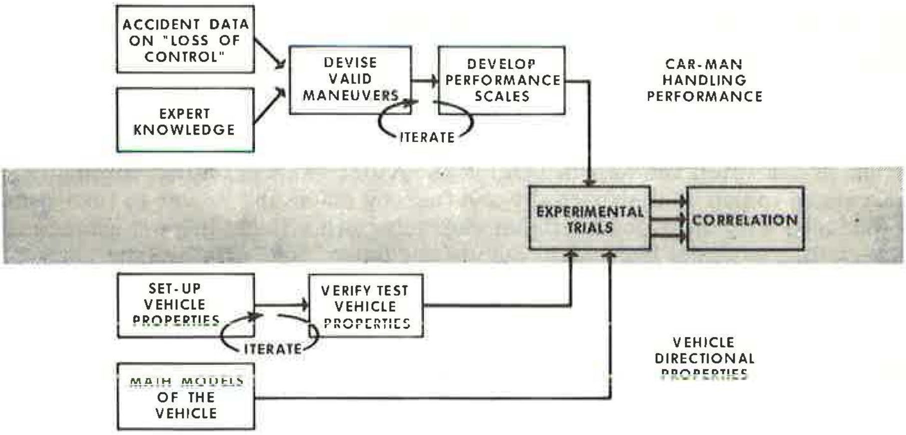

Figure 3. Research program.

We must determine the nature of the problem in concrete detail, by using all sources of expert knowledge, and through analysis of accident data. Better accident data than we now have must be obtained. This analysis should produce an exhaustive description and measure of the events and circumstances that typify "loss-of-control" incidents, such as skidding, unsuccessful recovery, and pavement drop-off. This result would guide the establishment of the set of measurement-based definitions of safe car-man handling performance. The development of techniques for measurement of handling behavior would be demanding, and the results controversial.

There is no obvious or natural scale of measurement for car-man handling performance. The definition of handling and the method of its measurement will be essentially synonymous. There is a variety of methods ranging from impressionistic descriptions to selected physical measures. For example, the observations made in each test trial may consist of a narrative description of the events that occurred. These descriptions could then be subjected to a content analysis and possibly to further statistical manipulation. On the other hand, the test trials may be run in such a way that descriptions or judgments are not sought; instead, such things as the top speed at which particular maneuvers could be carried through may be taken as the specific measure of success, or perhaps a tally could be made of the number of times that certain things occur, such as striking marker pylons.

Regardless of how objective the measure of handling performance or its analysis is, that measure will have to be derived from observed driving actions, and such a measure will probably be only moderately repeatable. There is a theoretical limit to obtainable correlations when measures are not repeatable, so a poor correlation might only reflect the lack of repeatability in the handling measure. And any imprecision in the vehicle response measure would further dilute the correlation. (Technically, the correlation cannot exceed $\sqrt{(r_{ii})\,(r_{jj})}$ where r_{ii} and r_{jj} are repeatability coefficients of the two variables X_i and X_j that are being correlated. However, it is not necessarily the case that conventional correlation coefficients or analyses based on them should be the objective of the research; this formula is merely given to show the effect of measurement imprecision more concretely.)

Furthermore, almost by necessity, any alleged measure of handling behavior will have to be obtained under practical circumstances that may produce only a crude imitation of real handling behavior. So, whether a resulting correlation is large or small, it would only reflect how well the vehicle response measures can predict this imitation handling, that is, until a valid correlation with accident statistics is determined.

Past experience leads us to believe that there is a broad region of vehicle motion parameter space in which there is no discernible difference in safety, although other criteria, such as preferences, might be more sensitive to parameter values. The experimental attack that probably will be most suitable is to find the threshold contour in multiparameter vehicle property space where car-man driving, or handling behavior, suddenly becomes hazardous. To find the threshold means that extreme maneuvers must be tried so the threshold can be crisscrossed often enough to map its contour. Even if conditions are arranged so that there is no danger, rapid learning by the experimental subjects and the spoiling of their innocence for future trials by evoking loss-of-control maneuvers will increase the practical difficulties of carrying out such a program. Concrete techniques for designing the appropriate experiment, conducting it validly, scaling the handling performance, and analyzing the resulting data are all open.

The experiment would seem to call for a response surface design with multiple dependent variables. Canonical correlation might be another analysis model. However, because of the nonlinear response associated with a threshold, these procedures may have to be modified, if indeed they can be used at all.

Many individual aspects of a program of this sort can be determined only as the program progresses. There will have to be flexible use of handling experts and ordinary drivers, of judged evaluations and objective measures. But, throughout, focus should be kept on the main purpose: correlation of safe car-man handling with vehicle properties.

The foregoing account assumes that there are maneuvers or car-man behaviors that are unsafe on their face; any observed correlation between them and accidents would be additional corroboration. The assumption is, however, open to dispute, if not in general, then at least in reference to individual types of behavior.

Independent Variables

There are equally difficult but less complex problems with the independent variables. Test vehicles must be provided in which a range of values for the experimental directional response characteristics is available for testing one at a time while holding all else equal (or its statistical equivalent in a factorial or response surface experiment design). Since it would be unlikely to find a set of existing vehicles that could be selected to meet this requirement, a number of experimental vehicles must be designed, developed, and constructed for the purpose. An appealing alternative is a variable-dynamics test vehicle in which electronically controlled actuators can alter the suspension geometry to produce the experimental vehicle properties. The most likely way to do this is with a car-borne analog computer that continuously calculates the simulated vehicle's path and then forces the driven test vehicle to follow just that path by servo control of its suspension (7). This also requires some development. And vehicle test facilities must be available to verify the parameter settings in either case.

A major difficulty will be encountered because the vehicle response is nonlinear in the region of parameter space most likely to concern us. The definition and description of vehicle characteristics in the nonlinear region will be difficult enough, but to provide a specifiable range of such characteristics in test vehicles will be even more so. The last section of this paper, covering some of the recent history of vehicle response modeling, will touch upon this.

The possibility of a fixed-base driving simulator suitable for this purpose seems remote except as a subsidiary tool for exploring some of the grosser hypotheses about human driving behavior. There are so many unspecifiable effects in real driving that it is hard to imagine how we could program or display them adequately for the purpose covered here.

A Simpler Program

The program sketched above may be more conceptual than practical; the very large number of independent variables, their interaction and nonlinearity, and the difficulty of producing valid experimental "near-accidents" might limit such an approach. There are some lesser, alternative approaches to the development of handling requirements. One of these would be to decide a priori, on the basis of experience and judgment, which typical handling-like maneuvers ought to be satisfactorily performable by a skilled driver under standardized and repeatable conditions. If a skilled driver can do it, then presumably the vehicle is capable of it. But if we assume that there are interactions between skill and vehicle properties calling for use of an unskilled driver, how do we specify his skill level so that repeatable and accurate results can occur? Another alternative, also a priori, is to select the vehicle directional response performance that should be achievable. However, all the considerations and warnings expressed earlier must be applied to any arbitrary selection of response criteria.

Mathematical models of the vehicle are in reasonably good shape today. While there has been only limited extension to the nonlinear case, which is important for safety-related response, the principal hindrance to their widespread application is the lack of a definitive criterion. A research program of the sort outlined here would provide the criterion and open the way for widespread use of computer runs as a means of expediting design and development. A related development touched upon earlier has been the search for a mathematization of the driver, in order to incorporate that into an overall model. This seems to be a search for a way to arrive at a criterion almost a priori; that is, the model would allow running numerous simulated handling trials and thus substitute for most of the research program described here. A functional relation between handling and vehicle properties would result from computer runs rather than from the empirical correlation obtained through observation of actual handling trials. These car-man models are certainly worth pursuing, but we believe that an experimental program is still required, even if only to validate the mathematical models. Experimentation is further required, however, to obtain estimates of normal variability because of the general desire to place requirements near the low end of the distribution of capability.

HISTORY OF RELATING HANDLING TO VEHICLE RESPONSE

Interest in defining the directional motions of automobiles by means of the formal mathematics of control systems engineering resulted from the rather incidental car-racing interests of aeronautical engineers. The earliest recorded attempts to derive equations of motion for cars in this country were made at Cornell Aeronautical Laboratory in 1950.

Before this, the analysis of car motion was limited to fairly simple descriptions of what was called "oversteer" and "understeer." The over/understeer parameter is still basic in the definition of vehicle motion. These terms, which are unique to automotive engineering, define what is normally thought of as steady-state gain of a control system. Cornell's entry into the field rapidly expanded the complexity and the completeness of handling description.

In 1953, Schilling (6) of the General Motors Research Laboratories published the results of a control systems analysis of two automobiles. He introduced the concepts of "free control" and "fixed control." These are test methods used to excite a moving car so that measurements of motion can be made for future analytical purposes. In free control, the car is thrown off-balance by jerking the steering wheel and then releasing it. The car will oscillate about a straight line while the steering wheel swings back and forth. The frequency and frequency decay are observed. This provides data on natural frequency and damping. In fixed control, vehicle motion is observed following a sudden step or ramp input to the steering wheel. The wheel is rigidly fixed after the motion. The two methods were observed to give different frequencies and damping for the vehicle. Generally, damping is lower for free control than for fixed control. The same appeared to be true of frequency.

Schilling derived equations of motion for his cars. In its general form, the equation was a fourth-order differential equation in which the yaw velocity was treated as the dependent variable, while the steering angle was used as the independent variable. The values of the coefficients were derived from known properties of tires, suspension, steering system, and inertia parameters of cars. By knowing such measurable factors as the car's mass, wheelbase, and roll spring rate, its motion in yaw could be predicted. This was a significant step forward in the description of car response.

Car behavior was clearly different for the free control and the fixed control cases. This introduced a perplexing problem. What would the motion of the car be if a human hand were placed on the steering wheel? A human hand, even when considered to be a passive element, would produce a third type of vehicle motion. The mathematical definition of vehicle motion from known vehicle parameters is muddled by the human controller, whether he is inserted in the control loop as a passive or as an active element.

By 1956, the study of vehicle motion had become sufficiently advanced that Whitcomb and Milliken (9) were able to publish some simplifying assumptions and a rather comprehensive compendium of relevant vehicle parameter values to be inserted in the differential equations of motion. The equations of motion were extended from the case where motion is initiated with the steering wheel to those cases involving externally applied side forces. One- and two-degrees-of-freedom models were discussed. Schilling's one-degree-of-freedom model expressed yawing motions as the sole output. The sideslip degree of freedom was added in the Milliken model, and rather than being of fourth order, he used as a model a second-order dynamic system. He considered the second-order model adequate for design purposes.

Interestingly, Whitcomb and Milliken made no attempt to insert a driver in their models. However, design objectives were made explicit. Rather than trying to hammer the human into a formal mathematical paradigm in order to prove a point, their design objectives were based on a general understanding of human control behavior. Since these objectives are seen in the writings of later investigators, it is worth quoting some of them here, even out of context:

> . . . to provide adequate response of the vehicle to control.
>
> . . . to minimize the response to external disturbances.
>
> . . . the amplitude of the response to the control input that driver is able to apply should be adequate for whatever conditions the automobile may be expected to encounter in normal use.
>
> . . . there should be no conditions for which the response to the minimum control that the driver is capable of resolving is so great that undue attention and effort on the driver's part are necessary to prevent the vehicle from becoming uncontrollable.
>
> . . . it is very important that the response of the vehicle per unit of time and the time to attain steady state be coordinate with the driver's response time, so that adequate control may be obtained when needed, and so that unwanted responses may be eliminated.
>
> . . . The amplitude of the transient response should desirably not exceed the steady-state value . . . a damping ratio of approximately 0.6 to 0.7 provides a response that will not significantly overshoot the steady state and also provides the minimum response time.

Segel (7) continues along this line in a 1965 discussion of a variable-stability automobile. One of the features that would be brought under experimental control would be the ability to alter the frequency and damping ratios of the vehicle without changing static (steady-state) sensitivity. Segel also stated that the test vehicle should allow the experimenter to determine the following:

> To what extent do the turning and rolling properties of an automobile influence subjective opinion and ratings of handling qualities?
>
> To what degree can objective measurements be made to support and verify subjective opinion?
>
> More specifically, what are the static and dynamic properties of the fixed-control automobile that make for good handling qualities in accordance with criteria that have been established by some rational and valid procedure?
>
> What are the static and dynamic properties of the free-control automobile or what are the properties of a steering system that make for "good" handling, assuming the standards for judgment have previously been defined?

Segel's phrasing seems to indicate a need to relate the performance evaluations made in actual on-the-road trials that are traditional to automotive development practice to "some rational and valid procedure." The "rational and valid procedure" to which he is referring may be that used by Bundorf, his coauthor. In a second part of the paper, Bundorf describes a handling test that measures course-keeping behavior as a criterion of handling performance.

By the mid-1960's, the art of relating vehicle parameters to the transient and steady-state motions of cars had become refined. Nordeen (5) published a parameter study showing the effects of small changes in chassis parameters on the response of the vehicle. Bergman (1) presented an exhaustive analysis of understeer-oversteer properties, substantiating theory with experimental data.

An SAE seminar to standardize definitions and terminology applying to all aspects of vehicle dynamics was reported by Bidwell (2) in 1964, and the new terminology was published in the SAE Recommended Practice, Vehicle Dynamics Terminology—SAE J670A. The revision was limited to descriptive terminology. It made no mention of criterion levels to be achieved.

Milliken has often expressed the opinion that there has been an overly tenacious fascination with the measures of steady-state vehicle response (e.g., steady-state understeer). He feels that this response property is unnoticed by the driver, just as airplane pilots do not significantly respond to the static directional stability (or weathercock) item in the equations of motion of those vehicles. The handling expert forms his subjective impressions on the basis of a large number of fixed and free transient responses due to various inputs (steering position and force, road camber and roughness, wind) and evaluates the results; but he seldom evaluates over/understeer as such. Milliken has pointed out that time delays, initial slope, first overshoot, damping ratio, and final value are all acceptable measures of transient response that are highly visible to the human controller.

With these techniques, it is possible to describe the response of cars in terms of linear control theory. The maneuver cannot be too severe, however. Milliken found that linear theory works up to 0.3 g. He emphasizes that "if one says one is only interested in breakaway at the rear end with various types of suspensions—then the linear theory has obvious limitations." Nonlinearities are clearly seen in test results.

Since it has been observed that quite a few drivers do take curves at lateral acceleration levels of 0.3 g and beyond (3, 4, 8), this consideration is more than academic (see Fig. 4 for a summary). Indeed, it is well into the nonlinear region, at rather high lateral g levels, that most of the relevance to safety is probably concentrated, and where the study and analysis effort is therefore required.

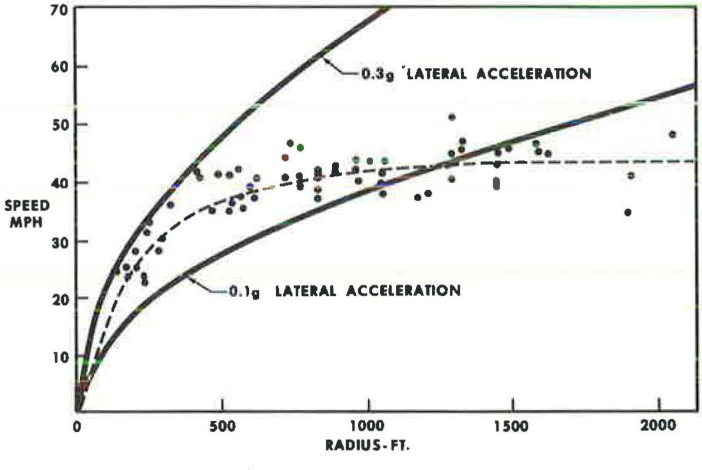

Figure 4. Average speed on curves.

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Discussion

JOSEPH B. BIDWELL, General Motors Corporation—It is first important to reemphasize the point made by the authors distinguishing handling performance from other measures of vehicle design or response characteristics. Broadly, handling means the path and velocity control performance of the car-driver combination. This definition in itself does not indicate how handling performance is measured. Vehicle response parameters, on the other hand, have been defined in quantitative fashion so that we can conduct specific tests and obtain measures of response behavior (10). Handling performance may be similarly defined more specifically in terms of test procedures and quantitative measures of performance. These tests must involve the driver and driving tasks that can be evaluated by performance criteria, such as path error or elapsed time to complete a particular course. A large number of tests are required to completely characterize handling performance just as there are many response tests and response measures to characterize the vehicle dynamics behavior. The tasks must encompass the full range of operating circumstances encountered in driving. They must, therefore, include the normal low lateral acceleration tracking tasks as well as emergency maneuvers.

Because of the wide range of tests required to establish handling performance and the variability introduced by the driver in these tests, there is a great temptation to use vehicle dynamics tests as measures of handling performance. There clearly must be some relationship between vehicle dynamics performance and handling. The difficulty is that at the present time this relationship is not known, and because of the interactions of the dynamic response parameters, a simple relationship does not exist. There are a large number of combinations of vehicle dynamics response parameters that will result in essentially the same handling performance. As a result, we may find a number of vehicles which have quite different dynamic response characteristics, but which when operated by drivers will perform equivalently.

Once handling has been defined in terms that permit quantitative measurement, the remaining problem is to relate it to other variables of interest. Currently, there is interest in relating handling performance to safety. The authors have pointed out the difficulty of doing this in any direct fashion. Even if careful accident records were maintained over a long period of time, it would be extremely difficult to sort out the significance of handling performance from all of the contributing factors. We must, therefore, resort to judgment in deciding which handling tasks are likely to be most significant with respect to safety. Analysis of accidents indicates that emergency tasks are most likely to be safety-related.

Determination of the minimum performance level in the selected tasks to assure a desired level of safety will also require considerable judgment and experience. The use of vehicle dynamics parameters would result in either unnecessarily restrictive requirements or it would not protect against an unsatisfactory combination of response properties, depending on the individual criterion levels selected. For this reason, it appears necessary to use handling tasks in spite of the resulting experimental problems.

In summary, handling performance must still be defined in operational terms. Car-driver tasks and quantitative measures must be devised. The most difficult task is that of relating handling performance to safety and no strictly logical procedure is evident. Finally, handling requirements must be in terms of task performance rather than other response or design variables to assure the desired result without unnecessary restriction.

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10. Vehicle Dynamics Terminology. SAE J670a, Handbook Supplement, 1965.

W. F. MILLIKEN, JR., Cornell Aeronautical Laboratory, Inc.—The subject of this paper is a timely one particularly in light of the government's intention to promulgate safe handling standards for automobiles.

The authors have done a commendable job in summarizing the nature of the handling problem and in underlining many of the inherent difficulties in establishing requirements in this area. They then outline a "minimal program" that might support development of performance criteria for car handling and stability and determine "critical zones" related to safe highway operation. This is a very large order and by the questions raised by the authors themselves, one suspects that they are under no illusions as to the magnitude and success ratio of such a program. In fact, such problems as the establishment of safety relatedness, car-to-car variations in service, and meaningful safety tasks entail major research efforts in themselves. To acquire a better feel for the size the authors envision for this minimal program, I would be interested in obtaining their order of magnitude estimate of the number of separate correlations they envision between vehicle response parameters (or combinations thereof) and handling measures.

The development of safe handling standards is characterized by a large number of constraints and variabilities. Of the many mentioned by the authors, the fundamental constraint to a quantitative approach to standards specification is the inseparability of the car and driver. This inseparability enters every facet of the problem, such as trying to assess the driver and car contributions in accident data, devising quantitative specifications for the car alone, and envisioning compliance procedures.

In approaching handling standards some of the fundamentals of car control and development are frequently overlooked. The automobile as currently built possesses no inherent path stability. This characteristic is only made available to the system through the short-term navigational task of the driver. The emphasis that is frequently placed upon some particular vehicle property, such as understeer, is unwarranted, nor are particular amounts of various vehicle characteristics always desirable. What is good for one driver, task, and environmental situation, is not good for another. In short, the situation is one of compromise, and experience indicates that the best automobile is one of well-balanced, well-tempered design. This sort of thing may prove hard to specify in clear quantitative terms.

In my opinion there are questions as to the feasibility of correlating handling and vehicle response motions to the degree outlined in the suggested research. Certainly there is virtue in trying, and enough experience is already available to indicate that some success will be achieved. However, the development of a set of vehicle response parameter values that will uniquely define a "safe" car is unlikely. There are undoubtedly many combinations of vehicle dynamic characteristics that are equally satisfactory in the overall task envelope. Also, the vehicle response characteristics are a function of the vehicle concept and its component concepts (such as that of the steering system). We have been trying for nearly 20 years to come up with a set of aircraft response characteristics that define a "desirable" flying aircraft and, in this endeavor, we have made use of sophisticated flying simulators, i.e., variable stability aircraft. What we have learned is that the technique provides useful design guidelines, but that the numbers change markedly with design advance. Today, it is common to develop new specifications for new types of aircraft, and even then great reliance must be placed upon the judgment of experienced pilot-engineers during compliance testing. It seems to me that correlation studies of the type proposed by the authors will be most useful in providing insights into the nature of safe handling, which may then be integrated into the design process.

From the viewpoint of standards, there is something to be said for measuring overall task performance. Task performance is at a lower lever of abstraction than vehicle response and must, in any event, form the basis for a correlation of vehicle response to safe handling. Numerical measures for task performance have seldom proved successful for aircraft where it is difficult to determine path and where path is generally of secondary importance. However, for the automobile, path is of vital importance and, fortunately, it is easily measurable. I would conclude that we are going to have to develop satisfactory measures for a wide variety of task performances regardless of what our design or standards philosophies may be.

There are, of course, many knotty problems connected with designing meaningful safety performance tasks. Accidents frequently involve operation at the limit of adhesion but recent experiments indicate that the average driver can be completely ineffective in these circumstances and, in fact, of his own volition seldom operates at a lateral acceleration in excess of 0.35 g. In the limit-of-adhesion type of emergency, the average driver may freeze on the controls, throw up his hands, or engage in an effective open-loop control action. In any event, the "average driver" is a difficult concept to work with, and in the limiting situation the traditional closed-loop models do not represent the facts.

The authors have quoted various views put forth by Whitcomb and myself in earlier publications and communications. Our view at the present time might be summarized by stating that we recognize the driver as the intelligent element of the system with a responsibility for guidance and that the vehicle enters the picture by providing the driver with a suitable tool for exercising the guidance function. Thus the vehicle can be thought of as a sort of backup for the driver by

1. Minimizing external disturbances,
2. Insuring satisfactory response characteristics,
3. Insuring no major instabilities in the nonskid regime,
4. Providing satisfactory information flow to the driver,
5. Providing reasonable maximum lateral acceleration limits, appropriate skid warning, skidding characteristics, and recovery, and
6. Remaining consistent in its behavior with changing environmental conditions, such as rough road and wind.

In these areas the vehicle can assist the driver, but enhanced system performance can only be assured if the driver and vehicle are improved together.

DAVID W. WHITCOMB, Cornell Aeronautical Laboratory, Inc.—The authors have done a fine job in their introduction, explaining the problems of relating vehicle behavior to handling standards and handling standards to safety. There is no doubt from a qualitative standpoint that there is an influence, but we shall have difficulty in assigning any quantitative index unless the proposed research is completed. The need for studying the problem in terms of the car/driver combination is well stated.

The concepts of normal handling and emergency handling should be a valuable distinction in establishment of standards. I suspect that in the past the two classes have been thought of as only one. Normal handling probably includes "optimum handling," whereas emergency handling will be based on the absolute minimum requirement.

I am impressed by the description of the design and development programs used by Ford to produce cars of acceptable handling. Truly this is an iterative process, but it does seem to be effective. The ten grades of handling are the beginning of a quantitative standard. It would be interesting to know what features of the car and its response produce a specific rating.

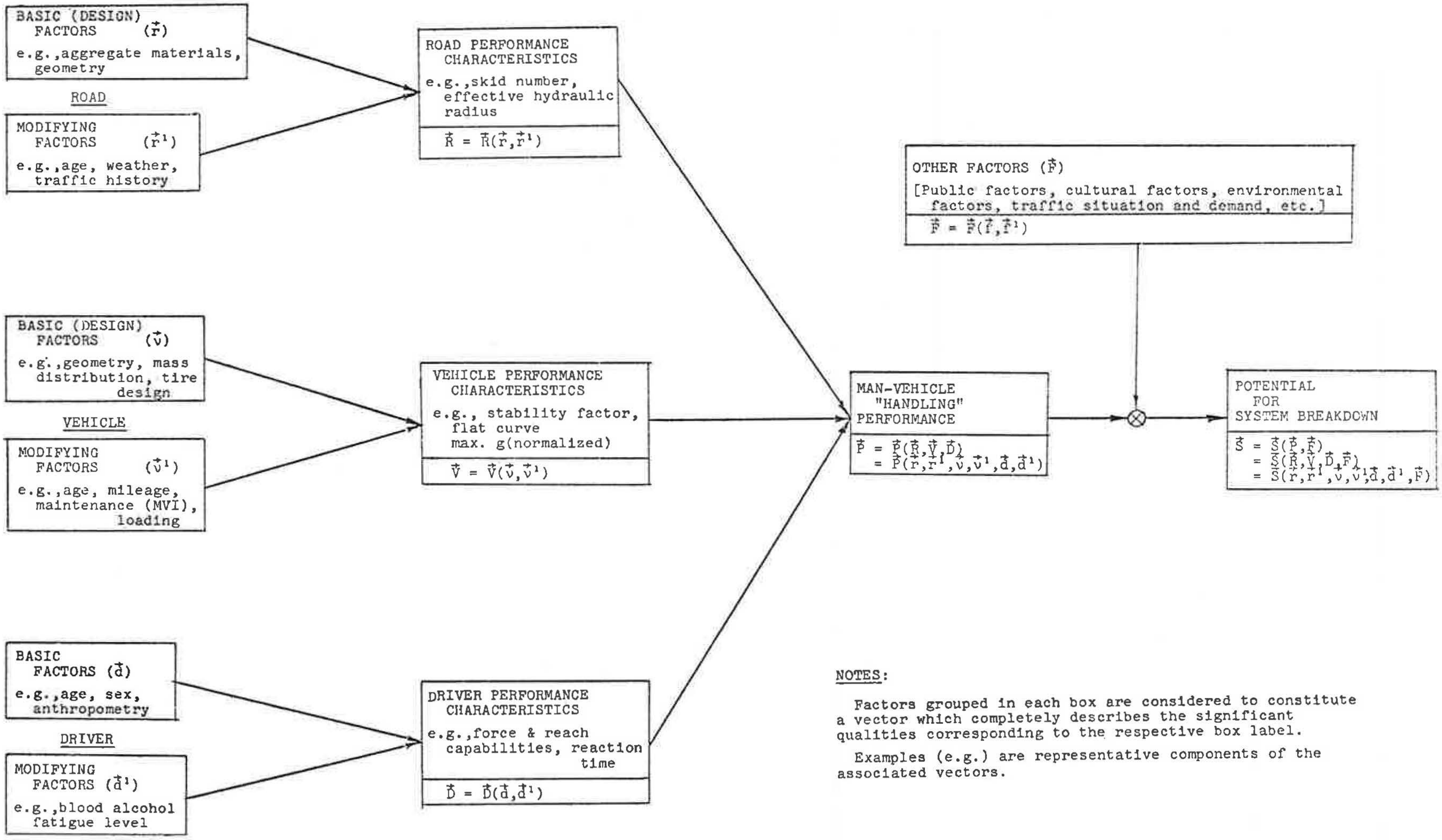
When testing for vehicle response parameters, the observation is made that the driver is an automaton during these tests, because his only task is to operate the instrumentation and insert the inputs. This I believe will lose some useful data unless the driver makes subjective evaluations of the motions. The crux of the problem is that we want criteria for industry guidance that will delineate their design and development responsibility in terms of the vehicle. But these criteria must come from research on car/driver evaluations.

I agree that from the safety aspects there are a whole complex of handling qualities that may be acceptable for safety considerations. This suggests that there are minimum handling properties associated with safety and others that might be classed as optimum qualities, i.e., those that please the driver. The handling experiments should use professional as well as novice drivers. In aircraft handling quality research, the professional pilot has been found to be a very good interpreter of novice pilot handling requirements. In the automobile we know that the novice (or most drivers) seldom drive to the limit of performance in terms of the maximums the vehicle is capable of.

A word about "fixed control" and "free control," which are described as empirical methods of analysis. These concepts are widely used in analyses of airplane stability and control. Fixed control implies that the stability and control is analyzed in terms of a control surface deflection as the disturbing input. Free control means that the input is a force or moment applied to the surface. The surface deflection will differ from that of the fixed control regime. Applied to the automobile, "fixed control" considers the input to be a deflection of the front wheels about the kingpin axis. "Free control" implies that the input is a torque applied to the steering wheel. The inertia, damping, and elasticity of the steering system are involved in the response to the torque input. (Another fixed control regime would involve the application of a steering wheel rotation. The effects of steering system inertia and damping are removed, and only the elastic properties will influence the value of kingpin angle.)

The example analyses in Whitcomb and Milliken (9), while somewhat limited, were offered to show what could be accomplished with a simplified linear approach, and to explore the relative effects of vehicle design parameters on the motion. The real design would, of course, entail a more complex set of equations of motion.

LEONARD SEGEL and HOWARD DUGOFF, Highway Safety Research Institute, University of Michigan—Versace and Forbes have presented a candid, comprehensive, and interesting account of the procedures employed by the automobile industry for the treatment of car-handling characteristics in the overall design/development process. They have also attempted to consider the vehicle handling phenomenon in a more general context, and have addressed a set of very basic and difficult research questions concerned with the relationship between car handling and safety. The conclusions they reach in this latter connection are largely negative, and the research program they propose, to relate "safe car-man handling performance" to "objectively measurable vehicle control properties," reflects the viewpoint of the vehicle developer (rather than the highway



NOTES:

Factors grouped in each box are considered to constitute a vector which completely describes the significant qualities corresponding to the respective box label.

Examples (e.g.) are representative components of the associated vectors.

Figure 5. Elements of pre-crash safety.

safety researcher) in its preoccupation with subjective car-man handling evaluation. We will argue here that a precise definition of the "handling problem" (in terms of overall man-vehicle-highway system performance) reveals that the subsystem performance concept generally identified as "man-vehicle handling" can be viewed as being extraneous to the real-world relationship between vehicle design and safety, the relationship of ultimate concern.

Figure 5 illustrates the variables and factors contributing to that quality of the road-vehicle-driver system that the authors characterize as "presumed safety," and that we choose to denote as "potential for system breakdown." We assume (with the authors) that this potential (or "presumed safety") is directly related to "actual safety" as would be measured by actual accident statistics. The reader may identify each of the elements in the central, or vehicle-associated line of this diagram with equivalent conceptual identities defined by Versace and Forbes: our "basic vehicle (design) factors $(\vec{v})$" with their "vehicle design," our "vehicle performance characteristics $(\vec{V})$" with their "vehicle directional response," and our "man-vehicle 'handling' performance $(\vec{P})$" with their "handling." The system element that we call "driver performance characteristics" is more elegantly termed "ergonomics" by the authors.

It is clear that the functional relationships between the various elements of Figure 5 are extremely complicated and at best imperfectly understood at this time. It is equally clear, however, that knowledge of each of these relationships is not a requisite to the improvement of highway safety through modification of vehicle performance characteristics. It is merely necessary to relate vehicle performance to accident data as gathered from the field. Research to this end would consist of direct empirical study of the function (see Fig. 5)

$$\vec{S} = \vec{S}(\vec{R}, \vec{V}, \vec{D}, \vec{F})$$

using accident involvement rates for $\vec{S}$, "averaging out" the effects of $\vec{R}$, $\vec{D}$, and $\vec{F}$ by employing extremely large data samples, and attempting to discern any significant variations of $\vec{S}$ due to variations in components of $\vec{V}$.

It should be immediately stressed that the research just described is straightforward in principle only. The effects of various components of the confounding variables $\vec{R}$, $\vec{D}$, and $\vec{F}$, may be so great as to represent "noise" that is of a greater magnitude than is the "signal" we hope to extract from the data, i.e., the effects of $\vec{V}$ components. It seems reasonable to assert, however, that if the influence of $\vec{V}$ is of a significant magnitude (i.e., if the influence of vehicle performance on safety is significant), then we should be able to discern it.

To perform a study such as previously described, it is not necessary to investigate either the relationship between vehicle response characteristics and handling performance, $\vec{P} = \vec{P}(\vec{R}, \vec{V}, \vec{D})$, or the relationship between system breakdown potential and handling, $\vec{S} = \vec{S}(\vec{P}, \vec{F})$. This is not to say that the vehicle manufacturer should not be studying these relationships; he should. In particular, he should continue to improve and systematize the assessment of subjectively measured handling qualities, since his product is purchased on a subjective basis. However, if the manufacturer is concerned with placing a scientific underpinning under the design decisions that may or may not influence the safety quality of his product, he must collect and analyze accident data from the field as the ultimate criterion of the safety quality of the vehicles he is introducing into the population at large.

GLENN G. BALMER, U.S. Bureau of Public Roads—It is gratifying to see research papers of this nature, and the authors are to be congratulated for their contribution to highway safety.

In the oral discussion of this paper that followed its presentation, a comparison was made between automobile drivers and pilots. It is important to recognize that the driver is, for the most part, from a generally unselected population with a minimum amount of driver training, as contrasted with pilots who have been screened physically and selected for intensive training prior to duty service. This contrast makes marked differences in their response performances.

JOHN VERSACE and LYMAN M. FORBES, Closure—We wish to thank the discussants for their comments, which, we believe, further illustrate the complexity of this topic. Bidwell called for defining handling in operational terms; i.e., handling should be defined in terms of the concrete, repeatable, objective operations or procedures that would be used to measure the degree of handling performance; the term "handling" would not be allowed to have any denotation beyond a definition couched in these specific terms. Both Bidwell and Milliken have stressed that the proper criterion of handling adequacy is car-driver task performance. The driving tasks and the associated measurements scales that would make up an operational definition of car-driver handling performance also enter as a critical part of our formulation, and are indicated in the upper part of Figure 3 and in the associated discussion.

On the other hand, Segel and Dugoff not only visualize a difficulty in developing a noncontroversial set of car-driver tasks that validly relate to safety—as well as the additional difficulty of then relating performance in these tasks to the underlying vehicle properties—but conclude that knowledge of these relationships is not even necessary. As a result, they are advocating an approach that short-circuits the need to develop criteria based on intervening task-performance variables; they would correlate accident statistics directly to the characteristics of the vehicles involved in those accidents. This is the most direct and most valid route—in principle. But, we doubt that it can produce valid conclusions until the present capabilities for accident data gathering and analysis are greatly improved.

Furthermore, the effects of road, driver, and environmental factors may not be "averaged out" just by taking extremely large samples of accident data. There are two kinds of confounding among the variables, and they would have to be accounted for, regardless of sample size. These effects are not just "noise," they are coherent "signals" interfering with the message that should be extracted from the data. First, although there are numerous vehicle properties, they tend to occur in characteristic combinations in the cars that are presently on the road. As a result of this interaction of vehicle parameters, conclusions cannot be reliably reached about them separately, or over a wide range of possible combinations that might become available in future designs. Bidwell pointed out that many combinations of these parameters may result in essentially equivalent handling (in terms of car-driver task performance). The second type of confounding is in the accident data. It results from the bias in the types of persons who drive particular types of vehicles (for example, the youth market, or the driver of the foreign sports car) and in the likelihood that certain types of vehicles and drivers are more prevalent in certain types of driving situations. It will take more than merely "averaging out" with large amounts of data to properly separate the effects of all the contributory factors.

Segel and Dugoff have understood us to place more reliance on subjective evaluations than we intended. In fact, we emphasized the use of car-driver performance measures, which might include such things as appropriately scaled path deviation derivatives and objectively estimated probabilities of successful car-driver task performance, as opposed to subjective appraisals of handling adequacy.

The discussants have emphasized different approaches, which perhaps differ as much with each other as with ours. We consider all the approaches as being basically valid, differing mainly in emphasis and practicality. However, evaluations based on different criteria could result in different theoretical and practical conclusions and suggest different actions. Task performance is probably the most practical criterion for testing cars, at least for now. But the engineer at the drawing board wants a set of quantitative factors to help him in designing a new vehicle long before he can have any drivable version available for task performance testing. These factors would be based on, among other things, the correlation between vehicle properties and the ultimate criterion, accidents—or, in the absence of unequivocal accident causation data, its surrogate, valid task performance. We, and the discussants, have been emphasizing safety-related considerations, but these are certainly not the only factors determining design criteria.