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,

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

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

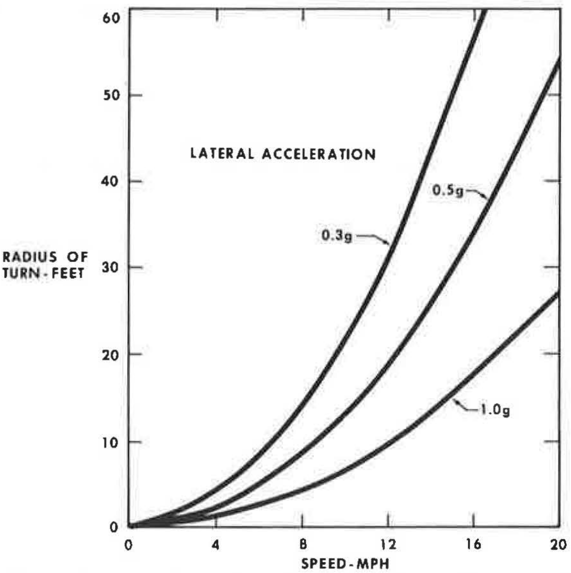

Figure 1. Lateral acceleration curves for various speeds and radii of turn.

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.

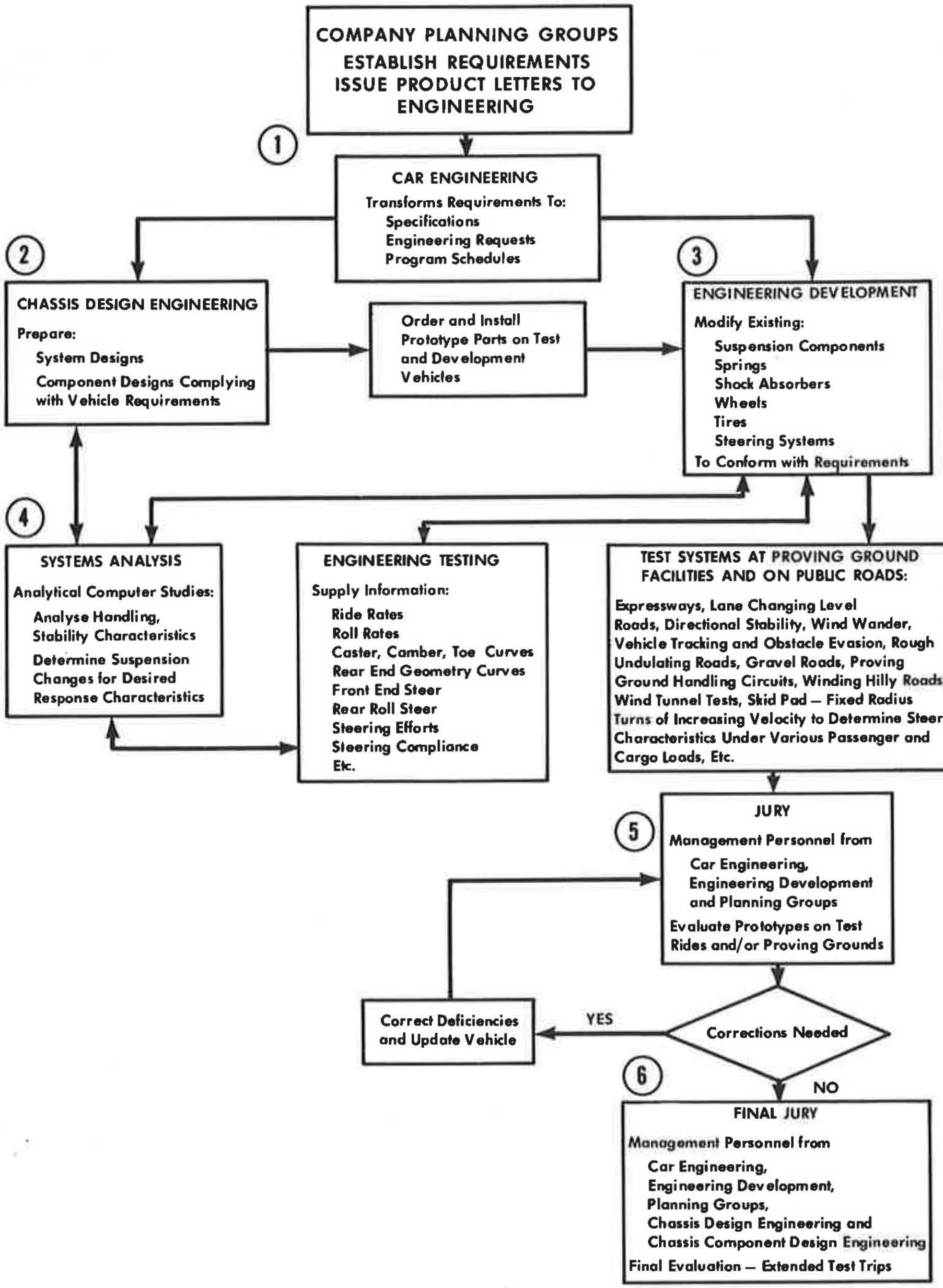

Figure 2. Procedures for developing acceptable handling and stability characteristics.

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.

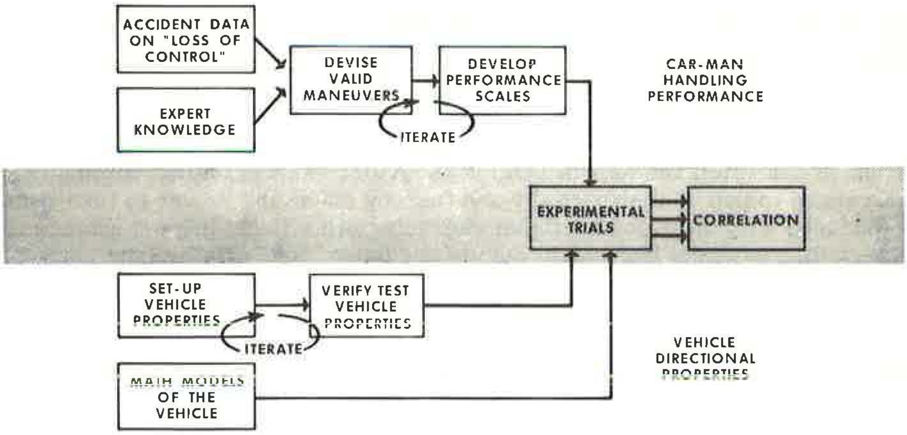

Figure 3. Research program.

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.

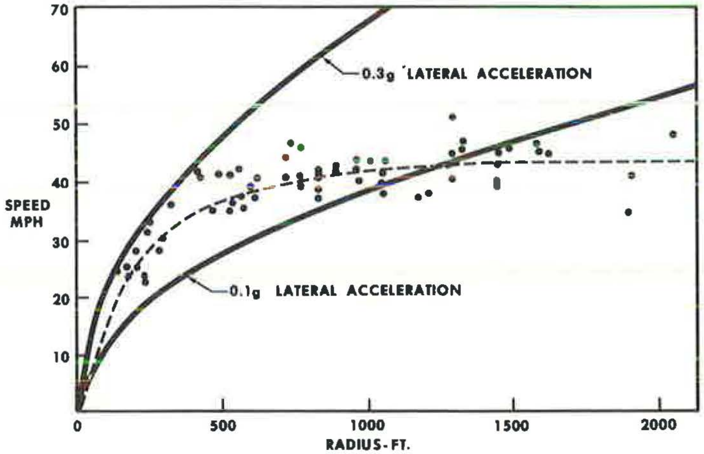

Figure 4. Average speed on curves.

REFERENCES

1. Bergman, W. The Basic Nature of Vehicle Understeer-Oversteer. SAE Preprint 65-957B, Jan. 1965.
2. Bidwell, J. B. Vehicle Directional Control Behavior Described in More Precise Terms. SAE Jour., p. 26, Feb. 1964.
3. Gray, P. H., and Kauk, W. H. Driver Operating Characteristics on Circular and Elongated Freeway Exit Loop Ramps. MS thesis, Dept. Civil Eng., Northwestern Univ., 1966.
4. Huber, M. J. Traffic Operations and Driver Performance as Related to Various Conditions of Nighttime Visibility. HRB Bull. 336, p. 37-50, 1959.
5. Nordeen, D. L. To Improve Car Handling . . . Look at the Chassis. SAE Jour., p. 58, Dec. 1964.
6. Schilling, R. Directional Control of Automobiles. Industrial Mathematics, Vol. 4, p. 64-77, 1953.
7. Segel, L., and Bundorf, R. T. The Variable-Stability Automobile. SAE SP-275, Feb. 1965.
8. Taragin, A. Driver Performance on Horizontal Curves. HRB Proc., Vol. 33, p. 446-466, 1954.
9. Whitcomb, D. W., and Milliken, W. F. Design Implications of a General Theory of Automobile Stability and Control. Institution of Mechanical Engineers, Automobile Div., London, Oct. 1956.

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.

Reference

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

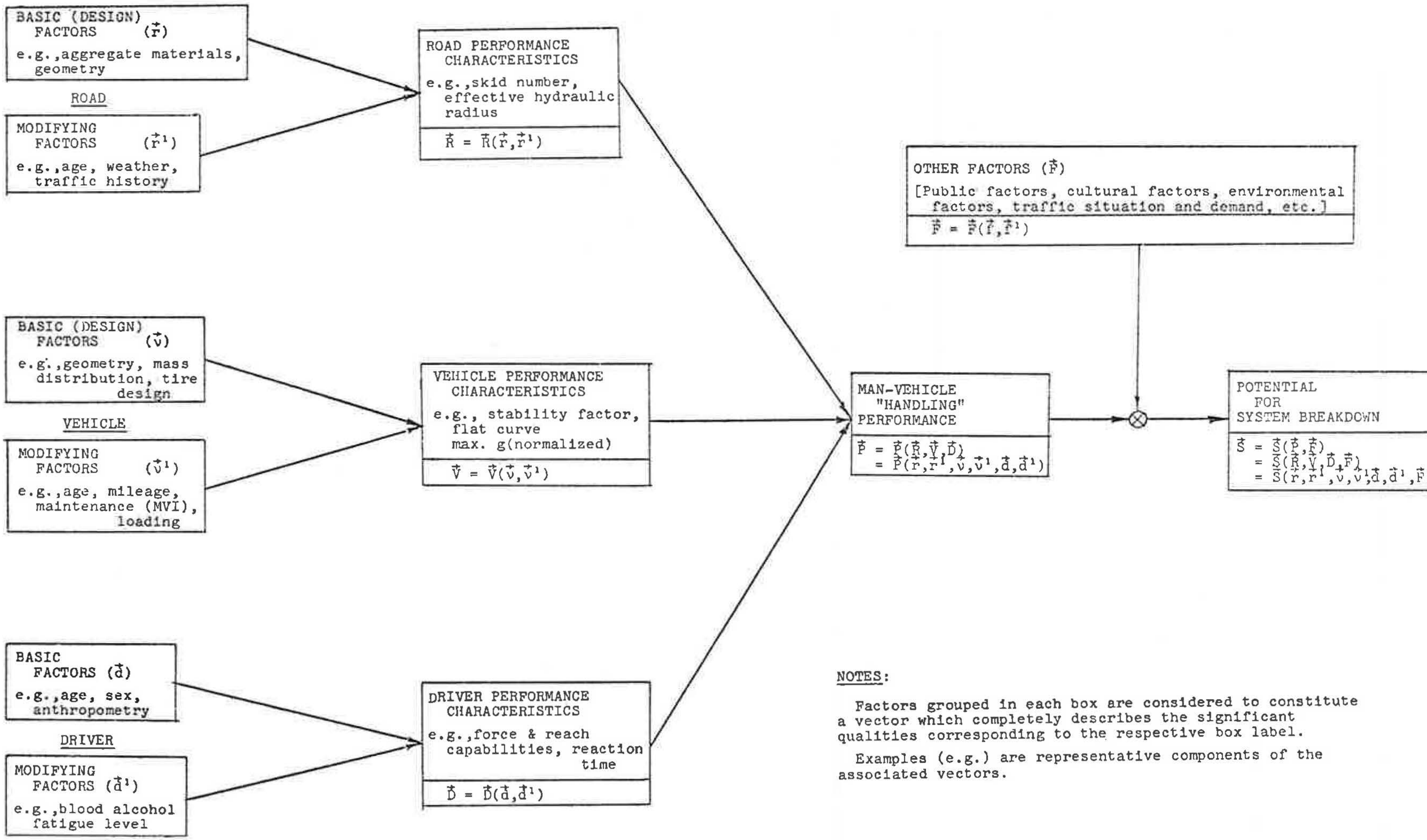

Figure 5. Elements of pre-crash safety.

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.