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FOREWORD

Although the vehicle is the common element in the three papers in this RECORD, the subjects discussed are quite diverse. Research findings presented here range from ways to improve seeing ability through windshields to automatic highways where driver vision may not even be necessary.

In the first paper, Fenton, Olson, and Bender describe a highway automation system design involving a vehicle that is manually controlled on nonautomated roads and automatically controlled on automated ones. They then give a progress report on various experimental and theoretical studies relevant to this design and point to a highly successful demonstration of a complete automatic vehicle control test on an instrumented highway at 60 mph.

The understanding of the problems associated with an automated highway system is further enhanced by the thoughtful discussions that follow the paper.

Plaster and Ozol investigated the origin and nature of dirt-forming windshield films and the most effective means of removing them. The findings and recommendations could prove extremely helpful in improving driver vision under most conditions. It will not greatly surprise most to learn that materials and procedures in use in many service stations produce less than optimum cleaning.

In the final paper, Young presents the development of an analytical model that predicts the response of an automobile passenger during vehicle motion of a general nature. The model is said to provide a tool for the highway engineer to use in modifying roadside structures and for the automotive engineer to use in designing safer interiors and restraint systems, to the end that crash injuries can be minimized. The model has thus far been validated for frontal collisions only.

CONTENTS

ADVANCES TOWARD THE AUTOMATIC HIGHWAY

R. E. Fenton, K. W. Olson, and J. G. Bender, Ohio State University

A considerable improvement in both highway capacity and safety can be achieved by highway automation. One design for such automation, which involves a dual-mode system whereby a vehicle is manually controlled on nonautomated roads and automatically controlled on automated ones, is first described. Subsequently, a progress report on various experimental studies relevant to this design is presented. The difficulties associated with two approaches to vehicle automatic steering are defined. A suggested partial solution that resulted in successful vehicle automatic steering at high speeds on the Interstate highway is presented. A scheme for automatic vehicle longitudinal control is outlined, and typical test data obtained from lead-car overtaking and emergency braking studies are given. The results of a continuing study of automatic merging are presented, and an approach to improving the performance of the driver-vehicle system during the interim period between nonautomated and fully automated highways is discussed.

•THE state of traffic conditions today—congested and inefficient roadways, a large number of accidents and fatalities, and an environment often defaced by seemingly endless miles of concrete and noxious exhaust fumes—indicates the need for improvements in our highway system. Unfortunately such conditions will probably be worse in the next decade as it is predicted that 120 million motor vehicles will be registered in the United States in 1980 (1) as compared with the 97 million registered in 1967. If one should look farther ahead to the turn of the century, he would see vast sprawling supercities with populations characterized by adequate incomes, longer life-spans, and increased leisure time. One predictable result is greatly increased travel. The resulting traffic situation could be chaotic, unless some radical changes are instituted beforehand.

One such change, which would be at least a partial solution, is highway automation. Because it would result in a considerable increase in both highway capacity and highway safety, this approach has been examined by a number of researchers (2, 3, 4, 5, 6, 7). Also, in contrast with a purely public or mass transportation approach, one would retain the mobility, privacy, and freedom that are associated with the individual transportation unit.

The ultimate envisioned highway system would include the control of vehicles both within and outside of urban areas. In the former, following Lawrence (6) and others, the required behavior of individual vehicles would be determined by a centrally located computer(s) and communicated to each vehicle. In the latter, where one generally expects low traffic densities, a decision-making capability located onboard a vehicle would specify the required behavior of that vehicle. It is obvious that a control transition, which might be adaptive in nature, would be required between such control states.

An individual vehicle would enter the system at a special entrance point where—if it passed a rapid automatic checkout—the driver would indicate his destination, and the vehicle would move to an entrance ramp from which it would be automatically merged into the traffic stream. The traffic-stream velocity would be fixed by a central traffic controller and would be dependent on such factors as weather, roadway conditions, and

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the state of the traffic stream. Once in the traffic stream, the vehicle would remain under automatic control until the driver's preselected exit was reached. Then the vehicle would be guided off the highway and onto the exit ramp, and control would be returned to the driver.

Such a system must be introduced on a gradual basis so that it would be compatible with existing traffic at all stages. Thus, both equipped and unequipped vehicles would use the same highways (but not necessarily the same lanes) for years to come.

The design of this system can be conveniently divided into two intimately related parts—macroscopic and microscopic. The former comprises the systems aspect and relates to the optimum operation of an automated highway carrying thousands of vehicles and its interfacing with other modes of transportation. The latter relates to the required behavior of an individual vehicle in the system and the control and instrumentation necessary to achieve that behavior. The research discussed here deals with this aspect and is a review of progress toward the development of various subsystems for automatically controlling a vehicle on intercity highways. This review encompasses a discussion of two proposed techniques for automatic lateral control, an approach to automatic longitudinal control, one viewpoint toward automatic merging, and an overview of modified vehicle control-display unit for enhanced driver control.

AUTOMATIC LATERAL CONTROL

The design of an automatic vehicular steering system consists of three main parts:

1. The design of a suitable roadway reference for guidance,
2. The design of appropriate sensors so that the position of the vehicle relative to the reference can be determined, and
3. The design of the steering control.

Of the three, the development of a satisfactory roadway reference has posed the most severe problems to researchers, who have thus far concentrated their efforts on two systems. The most widely studied system consists of a single current-carrying cable buried in the center of a traffic lane. The resulting magnetic field (Fig. 1) is sensed by vehicle-mounted coils, the electrical output of which is used to determine vehicle location with respect to the lane center. Experimental testing of this one-wire system has been reported by General Motors Corporation in conjunction with Radio Corporation of America (3), the Government Mechanical Laboratory of Japan (4), and the Road Research Laboratory (Great Britain) (8). The second studied reference system, a two-wire system, is conceptually similar to the first; however, two cables separated by

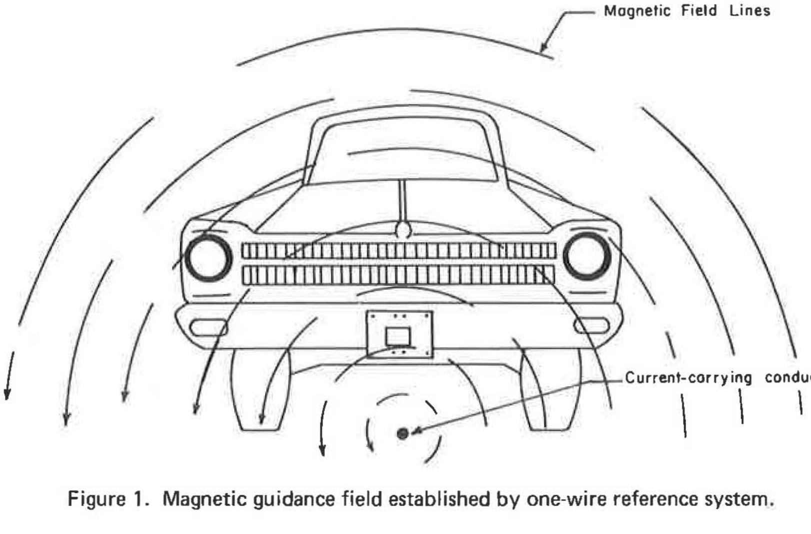

Figure 1. Magnetic guidance field established by one-wire reference system.

8 ft are used instead of one. Olson et al. (9) give the results of experimental tests of this system and a discussion of the problems encountered.

In theory, the guidance field associated with the two-wire system is linear over 7½ ft of lane lateral displacement as compared with approximately 4 ft for the one-wire system. This difference can be seen on roads without steel-reinforcing materials; however, when such materials are contained in the roadway or a steel bridge is present, the linear characteristics are greatly distorted. It is interesting both to compare distortion effects for each of these reference systems and to examine one promising approach for reducing such effects.

Toward this end, consider an automatic gain control (AGC) technique that can be used with both configurations. As previously reported (9), the slope of the steering error function varies as one progresses along a highway. (The steering error function relates the voltage output of the field-sensing coils to the lateral position of the vehicle with respect to lane center.) The effects of this variation—an uncomfortable ride and imprecise tracking—can largely be overcome by using AGC. Let the slope, m, of the typical error characteristic shown in Figure 2 be measured by a set of auxiliary coils on the vehicle. If the characteristic closely approximated a straight line passing through the origin, the time-varying system gain could be normalized by dividing the uncompensated error signal by this slope, because the gain is proportional to m.

A typical set of lateral error characteristic for the two-wire system, obtained at 1½-ft intervals along a section of steel-reinforced Interstate highway, are shown in Figure 3. Note that these characteristics do not closely approximate straight lines, especially in the region of zero error. Consequently, the slope of a given line is a function of lateral position and, at best, only an approximate correction is possible. Furthermore, it was observed that the amount by which the characteristics deviated from a straight line was a function of the section of steel-reinforced concrete under test. Figure 3 also shows the variation in average slope from one curve to the next, which indicates that the magnetic field strength varies as a function of distance along the roadway.

In contrast, the uncompensated lateral error characteristics for the one-wire system (Fig. 4) are much straighter, thereby making possible a much more precise gain correction. However, this linearity is achieved over only 4 ft, whereas it was approximately 7½ ft for the two-wire configuration.

The coil configuration for the one-wire system consists of four coils, two for measuring the position error and two, which are used with the first two, to measure the slope of the error function. The latter (or B coils) are mounted coaxially with the former (A coils), and both sets are mounted with their axes in a horizontal plane and lateral to the vehicle (Fig. 5).

The detected error signals as a function of lateral position are shown in Figure 6. The distance between the zero crossings of these two curves is equal to the spacing between the A and B coils (Fig. 4). The slope of the straight portion of both curves can

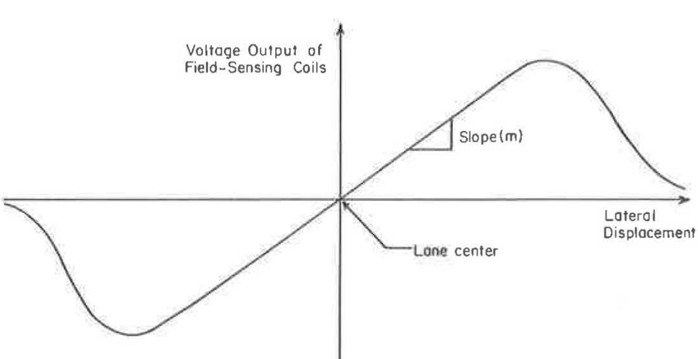

Figure 2. Typical error characteristic.

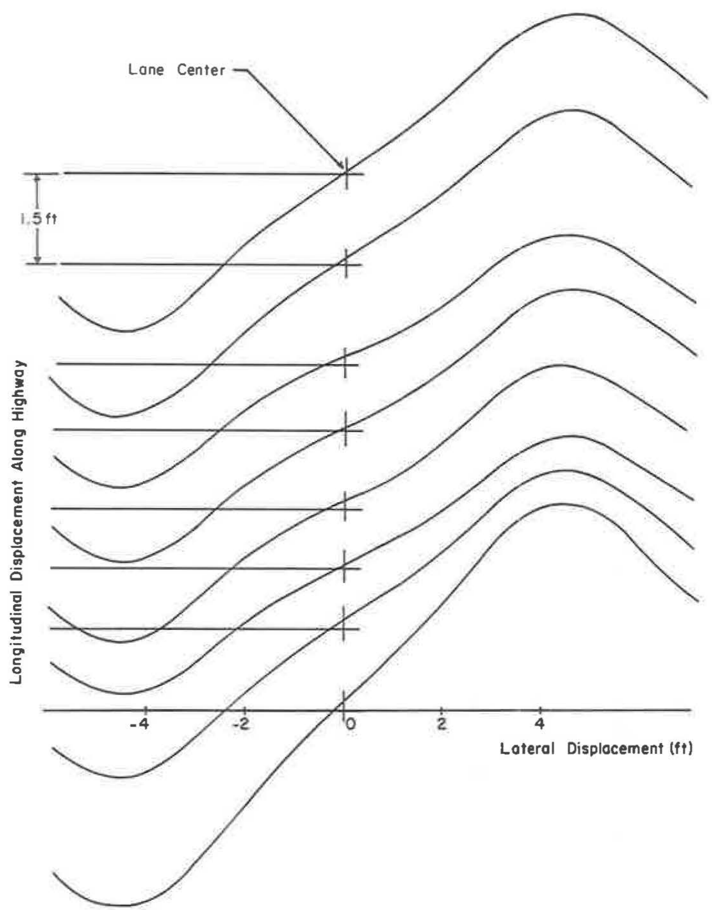

Figure 3. Lateral error characteristics for the two-wire system.

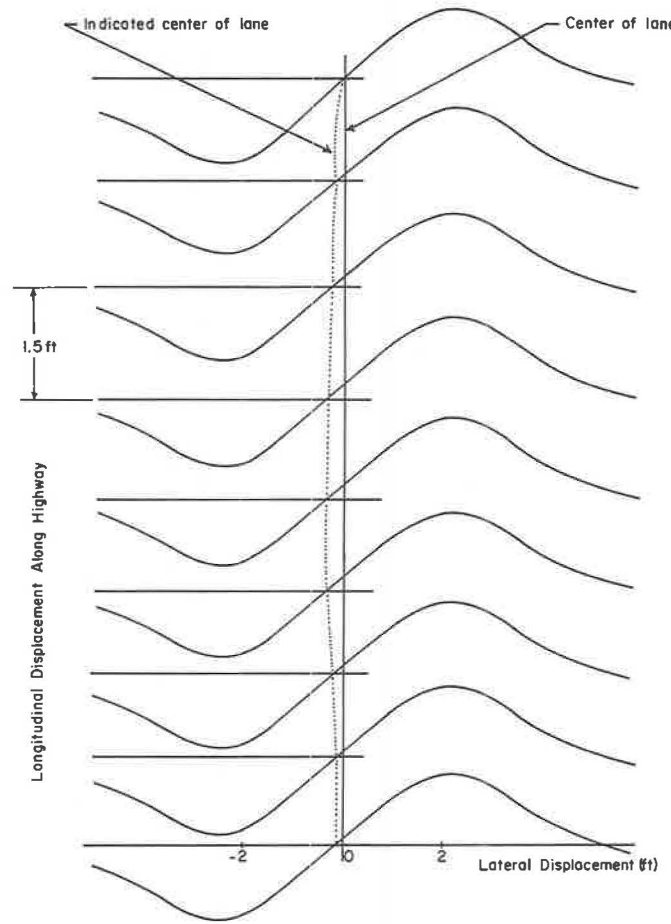

Figure 4. Lateral error characteristics for the one-wire system.

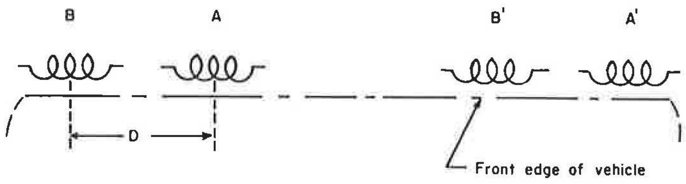

Figure 5. One-wire system coil configuration.

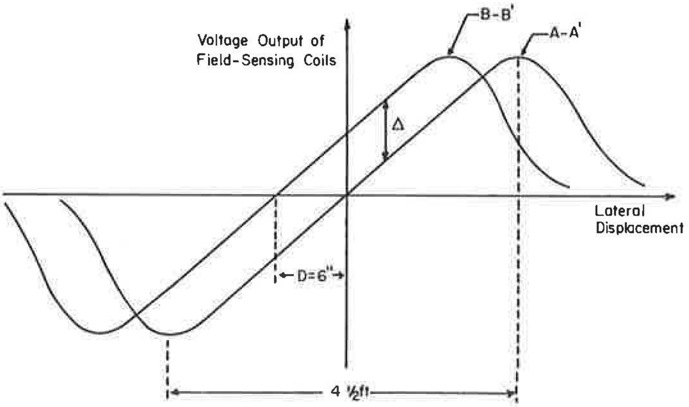

Figure 6. One-wire system error signals.

be determined by subtracting the output resulting from the A-A′ pair of coils from that resulting the B-B′ pair to obtain Δ. The slope is equal to

$$\frac{1}{D}\Delta$$

where D is the fixed distance between the A and B coils.

The ac component of the signal Δ was recorded while driving over a non-bridge area. As can be seen in Figure 7, three small peaks occur between major peaks. The major peaks are 60 ft apart and correspond to the expansion joints in the steel-reinforced concrete. The smaller peaks occur at the joints between the 15-ft lengths of the steel-reinforcing mesh. This plot clearly shows the substantial variation in system gain that would be present if the AGC were not used. The effect of the AGC in the one-wire system was to cancel out this variation far more effectively than for the two-wire case.

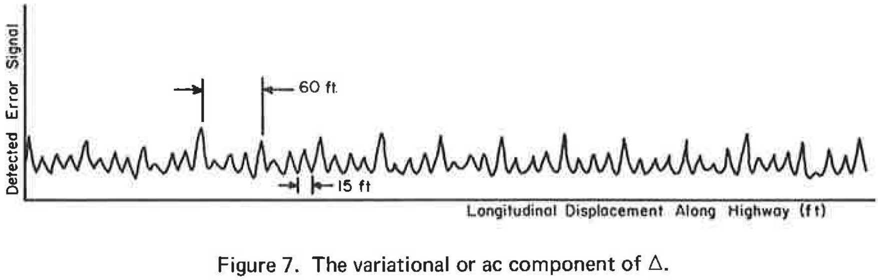

Figure 7. The variational or ac component of Δ.

The practical result was that a comfortable ride was obtained using the one-wire system at speeds up to 100 mph on nearly straight sections on Interstate highways, whereas such a ride was not obtained from the two-wire system for speeds above 60 mph. It should be noted that if such high speeds are to be attained on a curving highway, it may be necessary to use preview information as an auxiliary input to the steering system.

In essence, despite the limited 4-ft range of linear control with the one-wire system, as compared to approximately $7\frac{1}{2}$ ft for the two-wire system, the performance of the one-wire system was superior with respect to lateral tracking error and passenger comfort. This improvement can be attributed to the improved automatic gain control action.

Some insight was gained into another steel-reinforcing problem that is common to both the one-wire and two-wire systems and not correctable by automatic gain control techniques. This is the so-called null-shift problem. On the mile-long section of road used for steering testing, there were several areas over which the electronic center of the lane was shifted from the actual center. This is thought to be caused by an asymmetry in the steel reinforcing from one side of the road to the other. An example of this phenomenon is shown in Figure 4.

Even though the maximum offset in this area was only 3 in., passengers were subjected to a severe lateral acceleration. As might be expected, the severity of the acceleration was a function of speed and the direction and magnitude of the lateral tracking error before entering the offset area.

In an attempt to correct this situation, the wire was intentionally moved from the centerline of the lane in such a direction as to correct for the null shift. The results were gratifying in that only a slight lateral acceleration was observed over the area. This approach is currently being studied in more detail.

AUTOMATIC LONGITUDINAL CONTROL

Any system for the automatic longitudinal control of vehicles must be capable of coping with many different highway situations including lead-vehicle overtaking, steady-state car following, and emergency braking. One promising system for coping with such situations was suggested by Cosgriff et al. (10) who advocated a multimode controller that would control a following car with respect to the nearest lead car. Full-scale tests of a modification of this system are reported here.

The modified system can be conveniently described using the phase plane shown in Figure 8. Here the relative velocity, v, between two vehicles is plotted versus the headway, h. This phase plane is divided into a number of regions with a certain mode of control associated with each region. The regions are separated by switching boundaries, and thus, as a phase trajectory moves and crosses a boundary, the control mode

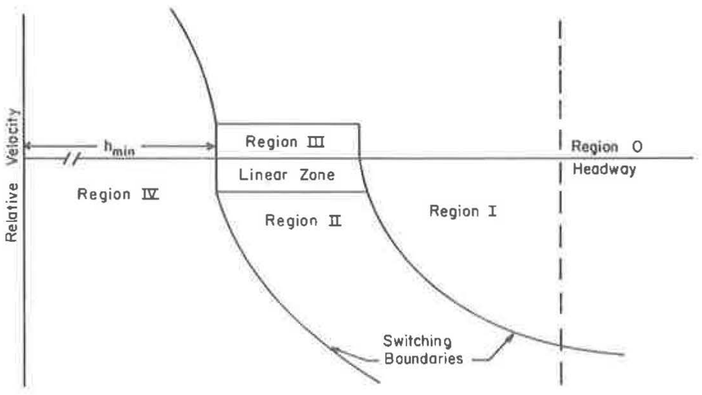

Figure 8. Regions of the phase plane.

changes. This change is made by a simple logic system that associates each point in the phase plane with a certain mode of control.

Bender et al. (11) have discussed the various modes of operation; here, only operation in Regions 0-IV is considered. When the controlled vehicle is in the right-most region (Region 0) of the phase plane, the control system behaves as a velocity regulator with the command velocity set either by driver or a traffic controller. When the controlled vehicle moves into Region I from the right, the command acceleration to the vehicle control system is zero, and thus, the vehicle would proceed at a constant speed until it crossed the switching line between Regions I and II. On entering the latter region, the vehicle is decelerated at a constant rate and brought into the linear zone (Region III). This constant rate is chosen so that a smooth and economical ride results.

In the linear zone, the control system functions so that the acceleration pv_2 of the following vehicle is proportional to the relative velocity, v, between it and the lead vehicle; i.e.,

$$pv_2 = \left(\frac{1}{\tau}\right)v \qquad \left(p \equiv \frac{d}{dt}\right) \tag{1}$$

If the headway were to decrease below h_{min} (Fig. 1), the following vehicle would be in Region IV where the possibility of a collision with the lead vehicle exists. The required control action is to decelerate the following vehicle at the maximum possible rate. It is clear that the maximum flow capacity of the system is fixed by h_{min}, which is a function of the average stream speed.

A late-model sedan was instrumented for automatic longitudinal control and tested in a variety of situations. The necessary state information—headway and relative velocity—was obtained via a mechanical takeup reel, or "yo-yo", which was attached to a lead vehicle (a 1969 Plymouth sedan) and the controlled one. [It is worth noting that several more practical methods for ranging on the lead car, which could be used in a nonexperimental environment, are currently under development. For example, Bentley and Associates have developed a vehicle-mounted Doppler radar for measuring the relative velocity between a vehicle and its nearest forward neighbor (12), while engineers at the Ford Motor Company are developing an infrared system for use in automatic headway control (13).]

Some typical results obtained from four overtaking situations are shown in Figure 9. The initial relative velocities were -4.5, -12.5, -16.0, and -18.0 fps, while the lead-car speed was held constant at 73 fps during each test.

It is instructive to consider one of these results in detail. A velocity-time history of the lead and following cars, corresponding to the case where the initial relative velocity was -16.0 fps, is given in Figure 10. Observe that when the controlled vehicle was in Region I, its acceleration was zero; however, when it crossed the switching

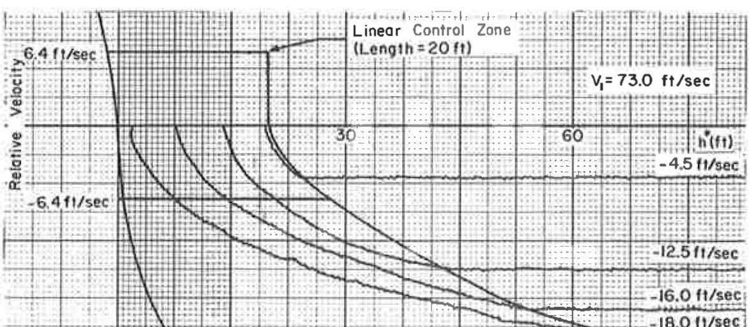

Figure 9. Various on-road overtaking situations.

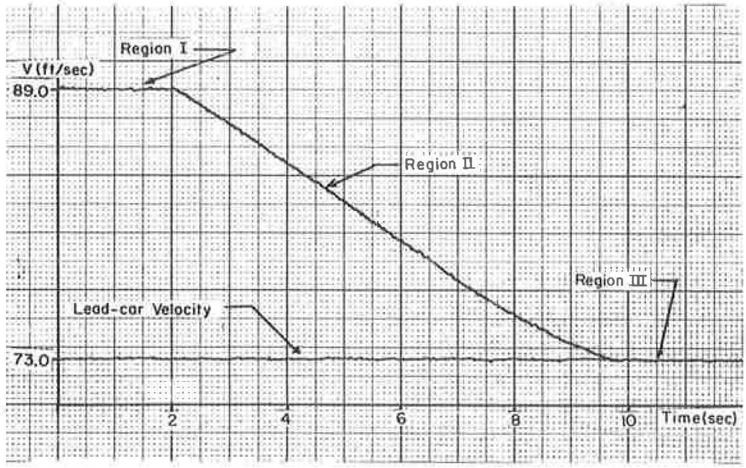

Figure 10. Velocity-time history of on-road overtaking situation (relative velocity of 16.0 fps).

boundary into Region II, it was decelerated at a constant rate and funneled into Region III. Its velocity then decreased to 73 fps, and a steady-state, car-following situation resulted.

The control associated with Region IV is shown in Figure 11. A controlled vehicle was initially in a steady-state, car-following situation with respect to a lead car when the latter was suddenly decelerated at a rate of 0.465 g. The controlled car quickly moved into Region IV and was decelerated at a rate of 0.392 g. This low deceleration was used so that the unopened highway used for testing would not be marred by black tire skid marks.

COMPLETE AUTOMATED CAR FOLLOWING

It seems appropriate to note that the individual studies in both automatic longitudinal control and automatic lateral control described here were culminated by a demonstration of complete automatic vehicle control. Here the instrumented test vehicle was programmed to automatically follow a lead car at an average speed of 88 fps over a $1\frac{1}{5}$-mile length of instrumented superhighway. The longitudinal control of the vehicle was in accordance with Eq. 1, and it was automatically steered using a wire system. The

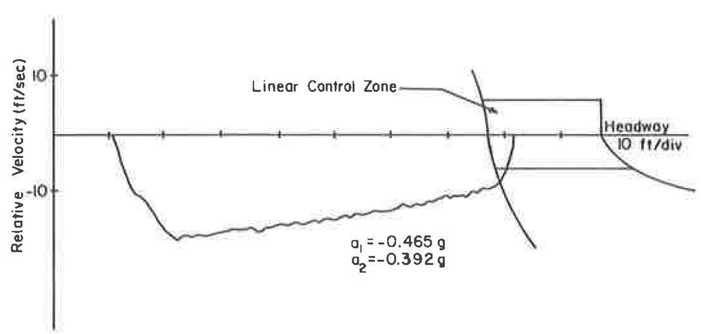

Figure 11. Maximum braking situation (a_2 = 0.392 g).

experiment was highly successful and is believed to be the first demonstration of a fully automated car-following situation at this high a speed.

AUTOMATIC MERGING STUDIES

The merging of automated vehicles into an automatically controlled traffic stream has two primary aspects: (a) the macroscopic or systems aspect, which is involved with both the simultaneous merging of a large number of vehicles at many intersections and the resulting effects on system performance; and (b) the microscopic aspect, which is concerned with controlling the behavior of a vehicle during the merging maneuver. Breeding (14) has discussed various aspects of the former, and the latter is briefly discussed here following the detailed presentation by Asghar and Fenton (15).

The nature of the required vehicle control is shown in Figure 12. An acceptable gap for merging into the mainstream traffic would be detected at Point A and a vehicle waiting at Point B would be released for merging. It would then be necessary to automatically control both vehicle lateral position and its velocity-time history so that it would merge into the detected gap at the proper point and desired time. It would be necessary, of course, to provide for a means of aborting this maneuver if an emergency situation should develop.

This approach is conceptually similar to one suggested by the Texas Transportation Institute for driver-aided merging on today's highways (16), which is currently under development by the Raytheon Company (17).

Longitudinal Control of Merging Vehicle

The longitudinal control of the merging vehicle has two major aspects: its control while on an entrance ramp and the changeover of this control to that required when the vehicle enters the mainstream traffic.

A major difficulty associated with achieving precise control of a vehicle on an entrance ramp is shown in Figure 13. The velocity-time histories that resulted when an identical control signal was applied to a test vehicle in two different environmental situations—no head wind and a 25-mph head wind—are presented. Note that in the former case 21.75 sec were required to reach the terminal speed of 100 ft/sec, while 30 sec were required in the latter. Because high flow rates can only be obtained for time headways of 1 sec or less (and thus, minimum acceptable gaps for merging must be some 2 sec), this variation poses a major problem. At the present time, tight closed-loop control of the merging vehicle is being experimentally studied as a means of overcoming this problem (15).

The desired states of entry of the merging vehicle into the mainstream can easily be determined from the phase-plane diagram shown in Figure 8. For example, one would not wish to insert this vehicle so that its state with respect to the lead vehicle were in Region IV because it would then be braked at the maximum value. If it were inserted into Region II, one would have the possibility that it would be next moved into Region IV

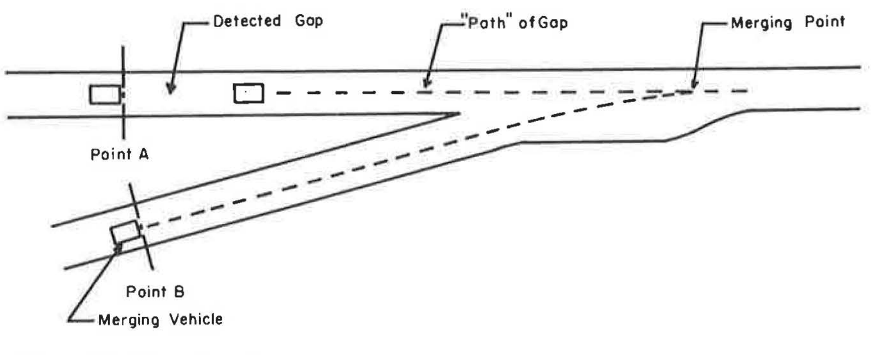

Figure 12. The state of a mainstream-entry ramp configuration when a gap is detected.

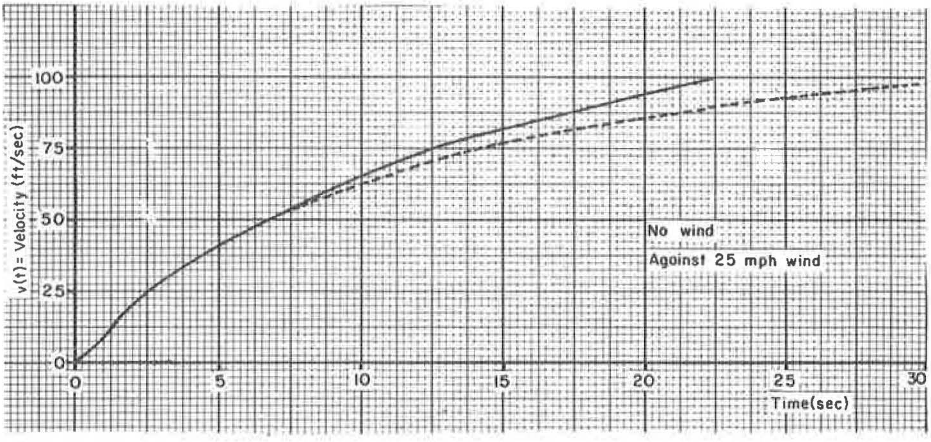

Figure 13. Velocity and distance responses of the test vehicle for a step input of 14 volts (wide-open throttle).

and fully braked. In addition, a relatively long acceleration ramp would be required as the speed of the merging vehicle at the merging instant would be greater than that of the mainstream vehicles. If all of the regions are similarly evaluated, it can be shown that the set of preferred states for automatic merging is as shown in Figure 14 (15). If a vehicle is inserted into the mainstream in one of these states, a smooth transition will result with no disturbances introduced by the merging operation.

Lateral Control of Merging Vehicle

It will be necessary to control the lateral position of a merging vehicle from the inception of a merge until the vehicle enters the mainstream traffic where lateral control is achieved via the system previously described. One simple method for achieving the initial lateral control is to use a one-wire system with a different current frequency (2300 Hz) than that used in the mainstream system (2000 Hz). This approach is currently being investigated, and preliminary results have shown that, as expected, the magnetic guidance field is distorted by steel-reinforcing rods in the merging lane in much the same manner as in the normal traffic lanes; consequently, the same problems as before must be overcome.

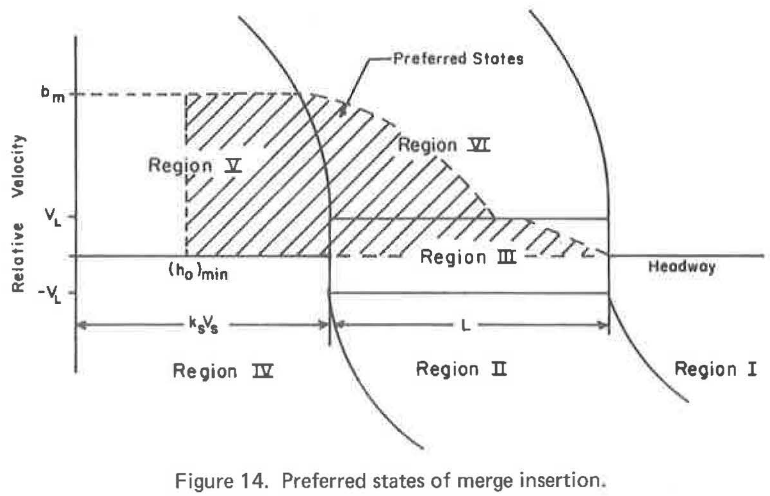

Figure 14. Preferred states of merge insertion.

MANUAL MODE STUDIES

Figure 15. Side-mounted control stick.

A manual mode will be required because a driver must control his vehicle on other than automated highways. It is also necessary to have an automatic system override capability so that he can regain control in emergency situations. After the automatic system is operational and has gained public acceptance, it might be desirable to remove this capability; however, it would certainly be necessary during the interim introductory period.

It was decided to use a single control unit instead of conventional controls for the following reasons: (a) the relative ease of obtaining compatibility between the automatic and manual modes if a control stick is used; (b) shortening the effective driver reaction time in emergency braking by almost one-half (18); and (c) the relative ease of incorporating a driver aid into a single control unit.

Several control sticks have been installed in a test vehicle and studied in typical highway driving situations. Figure 15 shows a test vehicle with one side-mounted control stick. To steer, one moves the control stick head to the left or right; to accelerate, one moves the stick forward; and to brake, one pulls it back. It should be noted that this stick was designed to eliminate cross-coupling between the lateral and longitudinal control motions. (It is important to mention that a potentially serious future problem is public acceptance of such a drastically different control device. Such a device is not an imperative for automatic system usage; however, it would probably be a considerable asset, especially during the evolutionary progression to fully automated highways.)

A driver aid—a kinesthetic-tactile display—was built into the head of this control stick (Fig. 16). The position of the shown metal finger is servo-controlled and gives a subject information concerning his instantaneous state with respect to the nearest lead vehicle. A number of highway studies have been conducted using this control stick-driver aid combination with one goal being to aid the driver, and thus, improve his performance so that it closely approximates that of the automatic system previously described (19, 20).

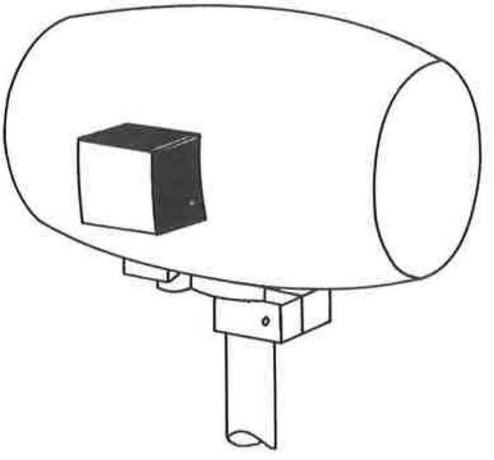

Figure 16. Kinesthetic-tactile display built into head of control stick.

Some success toward this goal has been achieved in one important type of highway driving—steady-state car following. In brief, following the complete description given by Rule and Fenton (20), a steady-state, car-following situation was first set up with a controlled vehicle automatically following a lead car that was traveling at an average speed of 40 mph and undergoing small random speed changes of some ±4 mph. Control of the following vehicle was exercised in accordance with Eq. 1 with $\tau = 4$. The velocity-time histories of both vehicles were recorded for 5 min, and a describing-function model was obtained from these data via time-series analysis. This model was of the form $V_2(j\omega)/V_1(j\omega)$ where $V_1(j\omega)$ and $V_2(j\omega)$ are the Fourier transforms of the lead and controlled car speeds respectively.

After the automatic system run, vehicle control was given to a driver who drove with the control stick and used information provided via the kinesthetic-tactile display to control his state with respect to the lead vehicle. Here again, the velocity-time histories of the lead- and following-car speeds were collected for 5 min of driving, and a describing-function model of the aided driver-vehicle system was obtained.

The experimentally obtained models are presented in terms of closed-loop frequency response plots of 20 $\log_{10} \left|\frac{V_2(j\omega)}{V_1(j\omega)}\right|$ and phase angle in Figure 17. The curves are remarkably similar, which is a strong indication that the dynamic behavior of the automatic system and the driver-aided system were comparable.

In a third run, vehicle control was switched from the driver to the automatic system and back again several times without the driver's knowledge. He did not notice any difference in vehicle handling as evidenced by his answers to routine questions, and apparently believed he was controlling the vehicle all of the time.

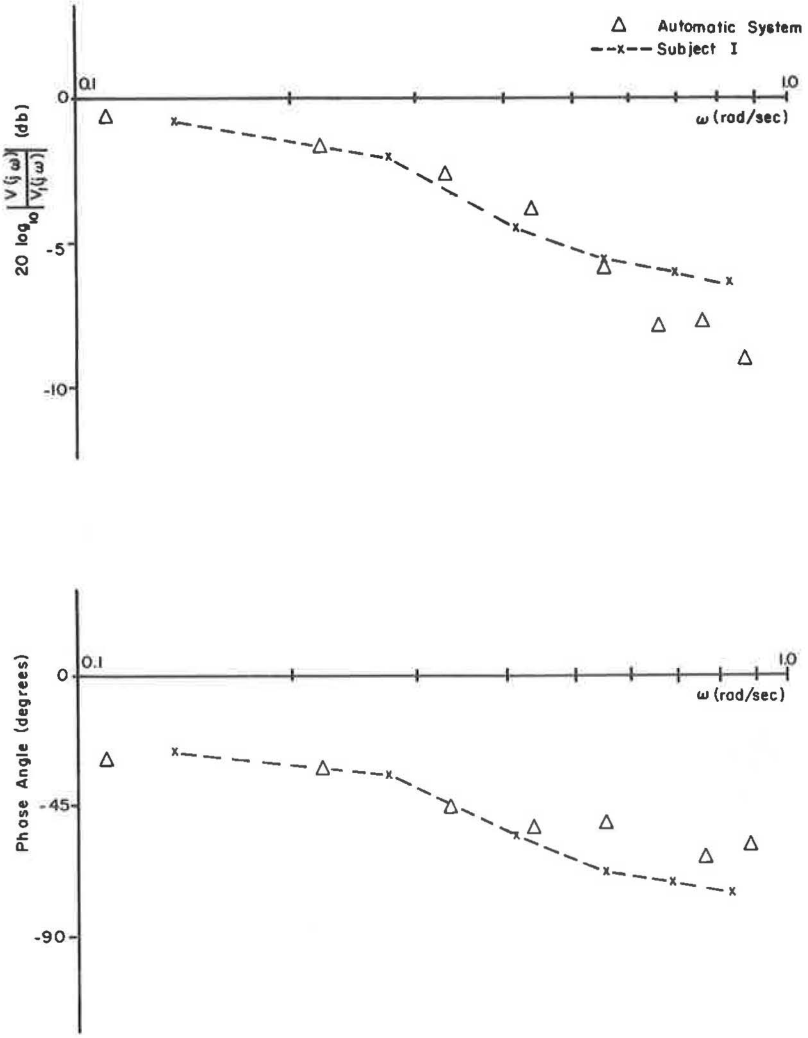

Figure 17. Describing-function models of automatic velocity controller and driver-aided system.

Because additional similar results were obtained, it does appear that compatibility between an automatic system and a driver-aided one can be achieved—at least under the limited conditions of steady-state car following.

CONCLUSIONS

There seems little question from the results presented here that vehicle automation is technologically feasible; however, a tremendous research and development effort will be required before a satisfactory automatic system is in operation. This effort must involve not only vehicle control studies, but also an intensive investigation of the present driver-vehicle complex, because the knowledge gained will be necessary for the proper specification and introduction of the control system components. Further, the need exists for intensive overall system studies so that optimum strategies can be chosen for headway spacing control, merging and lane changing, and the interfacing of automated highways with other modes of future transportation.

ACKNOWLEDGMENT

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Discussion

MICHAEL LENARD, Transit Systems Department, General Electric Company—The authors have presented their latest progress report on an extensive and long-standing program of highway automation research. Within the framework that was adopted for this program, the authors and their colleagues at the Ohio State University have pursued a course of theoretical and applied research, which has been marked by thoroughness, ingenuity, and technical excellence. Their pursuit of automated guidance and logitudinal control has now culminated in the first demonstration of completely automated car following (i.e., both guidance and longitudinal control) at a realistic road speed of 60 mph; a notable accomplishment indeed! The program is now approaching the point that it is realistic to discuss the expansion from theory and research to manufacturers' development programs and demonstration of a sample system. The authors point out several areas where work remains to be done before this can happen. This discusser would add a few more:

1. A rugged and cheap system for sensing the preceding car's movement is a key element.
2. Failure modes need to be studied: What are the worst combinations of lead vehicle trajectory and follower vehicle state and response?
3. In the response of a chain of vehicles, is exclusive dependence of control on the movement of the preceding vehicle adequate during an emergency?

In addition to such directly related developmental and research needs, the maturation of this program from the purely theoretical toward the prototype and demonstration phase implies an even more urgent need to examine the basis of highway automation. At what is it aimed? How is it going to be implemented? Is the dual-mode vehicle of the future going to be a replica of today's highway vehicles with an additional control package under the hood, or will there be some fundamental differences? This discusser would like to raise some of these broader questions on the basis of having examined performance parameters of such automated systems from the somewhat specialized point of view of collision safety in an emergency (21), and having also participated in preliminary estimation and control system costs for approaches to implementing automated highways (22).

The key goal of highway automation must be a severalfold increase in capacity over today's freeway lanes, combined with a safety performance, which, at the least, is better than the safest limited-access highways in existence today. Benefits of speed, comfort, convenience, and reliability will be realizable by automation, but by themselves they hardly merit the enormous costs involved. This means that unless safe automated highways of 6,000 to 8,000 vph capacity can be designed, the validity of highway automation may be questioned. Computer simulation of emergency response to a catastrophic failure in a automated lane (21) indicated that the desired level of safety is probably attainable at these performance levels. The results also indicated that this would not be the case if each vehicle were to respond to the preceding vehicle's movement. Instead, for these high-density flows, emergencies require the most expeditious and simultaneous controlled stopping of all vehicles to the rear of a perceived accident. One might then ask, if a control system with a capability of communicating with large numbers of vehicles simultaneously is needed (rather than a system based on preceding vehicle to controlled vehicle communication), does this then not suggest the adoption of a much simpler moving slot type of longitudinal control where each vehicle's motion is paced by a moving signal that is oblivious of surrounding vehicles' movements, except in an emergency? Such a system may be much less flexible than the authors' complex combination of four or more different control regimes. It may also be more predictable and thus more amenable to system control policies.

The choice between such fundamentally different control methods is closely related to the implementation of automated highways. The authors envision initial mixing of manually and automatically controlled vehicles on selected road segments, followed by eventual exclusive automated use. The moving slot control method is, of course, not suitable for this approach. The question has to be raised, is the design of highway automation made unnecessarily difficult by the requirement of mixed manual and automated traffic during initial implementation? An alternative approach is designing the first automated highway as a captive system, operated as a form of urban transit, the vehicles being designed for dual-mode capability that could be realized in a later implementation phase.

This discusser's studies (21) of sudden failures in a moving stream of vehicles ascertained that there is a significant safety advantage in being able to continue the movement of failed or colliding vehicles after the first one or few collisions. This continued movement will decrease the severity of collisions that follow—a significant advantage because, in a typical chain collision, the most severe collisions occur after the first few. To realize this advantage, vehicles may have to be anchored firmly into groove in a way that would permit movement after collisions. Other useful vehicle design features from the safety point of view may be shock-proof bumpers, and bumpers that would lock colliding vehicles together to improve their own and successive vehicles' safety. For such designs, electronic guidance is replaced by mechanical guidance and self-switching capability. The resulting vehicles would be more specialized with no retrofit capability for existing automobiles but, perhaps, an improved adaptability to pollution-free electric propulsion in the automated mode.

In summary, the authors' paper should be looked on as a description of one of the principal possible avenues to highway automation. Alternative approaches need to be developed to the same level of technical maturity. Some of the ingredients of these alternative approaches may be mechanical guidance, a moving slot method of control, initial implementation as an urban transit system, an emphasis on capacity and safety as principal design goals, and, perhaps, electric propulsion in the automated mode.

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LEONARD SEGEL, Highway Safety Research Institute, University of Michigan—The title of this paper implies that advances are being made toward attaining the automatic highway. This reviewer will argue that our progress toward achieving the implied goal is infinitesimal and, further, that there are substantial questions to be raised and answered with respect to the soundness of the general concept, namely, the automatic highway as envisioned in the subject paper.

The authors have addressed their attention to technical problems that must be resolved in the development of the automatic highway. Accordingly, they will, in all likelihood, feel that it is inappropriate for this discussant to suggest that (a) the macroscopic problem, which they set aside for others to solve, is the crucial problem, and (b) efforts to design the microscopic parts of the automated highway system are nonconstructive if one implies that these efforts are advancing us toward the presumed goal. This discussant sees no harm in developing guidance and control systems for automotive vehicles. His major objection is to the casualness with which the authors and others are willing to assume that the ultimate envisioned highway system would be a roadway complex that consists of both automated and nonautomated roads.

This discussant claims no expertise as a transportation systems analyst. Even without such expertise, it appears abundantly clear from the problems of guidance and control that the authors discuss in this paper that the automobile (namely, a personal, self-powered motor vehicle) in its present state of development does not constitute a sufficiently reliable mechanism to make the automatic highway (as conceived by the authors) a viable concept. For example, the authors have pointed up the difference in acceleration response to full open throttle as caused by the presence or absence of a head wind. Therefore, they suggest closed-loop control of the longitudinal trajectory as a means of implementing the high-speed merge maneuver. Have they considered the variability in acceleration performance that exists among all of the vehicles in our motor car population? Have they considered the variability in performance that results from lack of maintenance? The crucial shortcoming of the automatic highway as conceived by the authors, as I see it, is not that it must cope with a wide variety of vehicles of differing dynamic performance, but that it assumes that the vehicles can be personally owned or rented vehicles, properly equipped, but that can be used, abused, maintained, ignored, etc., by the user party.

I would argue that, as attractive as the idea may seem, the personally owned autobile does not lend itself to becoming a part of an automated transportation system irrespective of the provisions made for periods of gradual transition. There remains a basic incompatibility between the objectives of personal transportation, as achieved with a personally owned vehicle whose probability of breakdown is determined both by owner and user practice and attitudes, and the objectives of an automated system. The former provides freedom of action and choice and a flexibility of operation that minimizes the consequences for the remainder of the highway users should a breakdown occur. The latter presumably strives to achieve greater throughput, safety, and comfort, which is not only critically dependent on the functioning of the units added for automation, but is also dependent on the running gear and motive power of each operating vehicle.

Having raised my personal doubts as to the likelihood that we shall some day see in operation the system envisioned by the authors, I would like them to return my arguments, in kind, and, perhaps, assure me that I am an unreasonable skeptic. In addition to the doubts already expressed, I am continually bothered by the feeling that the phrase "automatic highway" is an unfortunate choice of words, and that we are tending to confuse oranges with apples.

Let me elaborate. The authors suggest that we need improvements in our highway system. Everyone would heartily agree. However, I suggest that instead of referring to a so-called highway transportation system, we should be talking about a personal transportation system in which households and businesses own or lease vehicles for operation on a road network that is provided by governments with the aid of tax moneys. The majority of us make a capital investment in a vehicle and then encourage our legislators to see that roadways are provided to allow us to go wherever we please with a minimum of inconvenience and hazard. Unfortunately, the inconvenience and hazards are increasing with time. The question then becomes, "How should we modify this personal transportation system to reduce the inconvenience and hazard and simultaneously increase the throughput, while at the same time providing for unrestricted origins and destinations wherein the traveler uses preferably one vehicle to go where he chooses at the time of his choice?" It is not obvious to me that for those portions of the trips where we conclude that benefits can be gained by introducing automation that the highway is a necessary or desirable feature of the system. Note that the term "highway" not only implies a broad ribbon of concrete, but also implies that the vehicle is supported by its own running gear and propelled by its own power plant. For any possible transportation system in which travelers remain in one vehicle and features are added that achieve the stated objective, the question must be asked whether the proposed solutions involving a capital investment in vehicles on the part of individuals and businesses are cost-effective in comparison with systems that are essentially equivalent in terms of freedom of choice but involve transfers between several different kinds of vehicles or conveyances in order to complete a trip. Note that the transportation system user, in this latter instance, is buying a service instead of making a capital investment in a vehicular device.

Obviously there are many implications to the above question as I have raised it. It is clear that the authors did not intend to grapple with these issues. But in view of the forum to which they have elected to remark on the advances being made toward the automatic highway, this discussant feels obligated to challenge the tendency to take the role of the highway for granted in future automated versions of personal transport. Automobiles serve the user remarkably well as long as the operator remains continually active as a tactician and decision-maker during the course of his journey and during emergencies. (Note that the tasks of maintaining a vehicle in a lane and positioning it in a stream of traffic are trivial compared with all of the other acts and decisions that a driver must make in order to adjust for the imperfections that exist in rubber, steel, concrete, and asphalt.) Certainly, we need to question whether the automobile, in its present form and state of perfection, can and should be part of an automated system. It is not incumbent on us to demonstrate that there will be real, cost-effective gains in personal transportation by means of the automated highways envisioned in this paper?

DENNIS F. WILKIE, Transportation Research and Planning Office, Ford Motor Company—The authors claim in this paper (as well as in previous papers) that a successful scheme for automatic lateral and longitudinal control of the vehicles in a large automated system can be developed independent of the overall system development. In their words, the microscopic problems can be separated from the macroscopic problems in an automated highway system. However, the microscopic problems of individual vehicle control can be divorced from the macroscopic system operation only if the approach taken to vehicle control is compatible with the macroscopic system operation, and if no unsurmountable problems arise when trying to extend the results on individual vehicle control to the operation of a large system. I contend that such insurmountable problems do exist in extending the car-following longitudinal control approach advocated by the authors to the operation of a successful full-scale system, and I would like to discuss this point further.

First, I would point out that essentially no distinction is made in the paper between the intercity and intracity operation of automated highway systems. In fact, there are very essential differences between the operating conditions one must face when developing an automated vehicle system for use in an urban environment as opposed to automating our intercity highway network. Certainly the flows are much more dense in an urban region than on the majority of intercity highways, the peaking effects of traffic volumes are much more pronounced, the constraints on available space for building entrance ramps and stations are more severe, and the network of automated roads would be much more dense in an urban region. Because the greatest problems to be solved in transportation are in urban regions, I would like to consider the system proposed by the authors in that context.

In an urban region, any sort of advanced or new transportation system will have to have a many-to-many collection and distribution capability in order to serve the diverse travel demands that have become predominant over the past 20 years. It is the need to serve such demands that dictates the need for networks of automated vehicles as opposed to disjoint automated corridors in urban regions (e.g., an automated highway network). In such an automated urban network, there will be many merges of high-speed streams of vehicles that must be safely accomplished, lane capacities much greater than those of existing freeways must be achieved in order to avoid the need for extensive new land acquisition, and the distance between entrances and exits will be of the order of 1 to 2 miles. Let us consider whether the microscopic approach to longitudinal control reviewed in the paper could ever be extended to a successful urban transportation system that would meet the above constraints.

First, the simple question comes to mind of who follows whom in an urban network carrying dense flows of automated vehicles? Further, how can high-speed merging of dense streams of vehicles be safely accomplished in the car-following approach without referencing the positions of the merging vehicle streams to fixed positions on the roadway? If such referencing to roadway position is needed, it becomes apparent that any possible advantages of a car-following approach are lost, and in fact it is difficult to imagine car following to be feasible with that constraint.

In addition, long strings of vehicles will occur in an automated network carrying dense flows, and the stability and sensitivity characteristics of a car-following longitudinal control scheme will be unacceptable in that case. Also, the emergency operation of a system based on car following would be unacceptable. With long strings of vehicles being controlled under this philosophy, is it reasonable to depend on the judgment and reaction times of the individual drivers (as suggested in the paper) to recognize emergencies and raise an alarm? On the other hand, will the system respond safely if it relies on the car following a failing vehicle to sense the erratic behavior and initiate emergency procedures for the whole stream?

Finally, consider the possible capacities of an automated system using the car-following approach to longitudinal control. Two of the authors recently published a paper (23) showing that, based on safety and comfort considerations, the possible capacity of an automated highway lane in steady-state operation would be about twice that of a conventional freeway lane. Certainly this does not represent a significant enough gain in capacity for an automated system as opposed to the present system.

Thus, without going into greater detail, I would simply stress that the critical problems in automated urban vehicle systems do not occur in steady-state operation; yet, steady-state car following is the only problem to which the longitudinal control results reviewed in the paper apply. The adoption of the car-following approach has resulted from a division between the microscopic and macroscopic operation of automated vehicle systems that I do not believe can be made, and, thus, I feel that this approach will not lead to a workable system.

Furthermore, because all of the results published here have been presented elsewhere, I assume that the authors intend this paper to be a review of advances toward highway automation, not just a restatement of their work. However, other groups (24, 25) working independently have proposed schemes for operation of automated systems that differ fundamentally from the car-following approach discussed by the authors, but alternative results have not been reviewed at all.

Acknowledgment

The discussant would like to acknowledge helpful discussion with R. G. Stefanek of the Ford Motor Company.

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R. E. FENTON, K. W. OLSON, and J. G. BENDER, Closure—The discussers have raised some interesting points, and we welcome the opportunity to comment on several of these.

First, we have stated that the design of an automatic highway can be conveniently divided into two intimately related parts—macroscopic and microscopic—and, in this paper, we discussed only the latter aspects. That does not mean that we have either divorced the two parts, as contended by Mr. Wilkie, or set aside the macroscopic part for others to solve as contended by Mr. Segel. Our efforts have encompassed both parts; in particular, we have performed computer simulation studies of various automated highway system elements and networks for studing various strategies of system operation. However, we did not intend to discuss such matters in this paper. A recent example of such studies has been published (26).

Let us now consider the statement by Mr. Segel that "... the automobile... in its present state of development does not constitute a sufficiently reliable mechanism to make the automatic highway (as conceived by the authors) a viable concept." The system that we described does not involve the automobile in its present state of development. Automotive reliability will not stand still for the next two decades—a fact that is abundantly clear in view of the increasing pressure exercised on the automobile industry by Congress and the Department of Transportation, and the indirect effects of consumer advocates such as Ralph Nader. We can reasonably expect the development of the automobile to continue at an accelerated rate so that, in some 20 years, it will be a much safer and more reliable means of conveyance that will be capable of more consistent controlled performance under a wide variety of operating conditions. One of our primary concerns has been the specification of conditions under which such consistent performance can be obtained in various highway situations. One study of the inconsistencies to be expected in the controlled performance of a contemporary vehicle, together with a technique for overcoming these inconsistencies, has been reported (27).

The vehicles, which would be used on automated highways, would have to meet certain minimum performance specifications. (The problem would be greatly simplified if all vehicles had the same rated performance, but the imposition of such a constraint appears unlikely.) A vehicle owner would have a strong incentive to properly maintain his vehicle, because if it could not pass an automatic checkout before entering the highway, it would not be allowed to enter.

We are conducting all of our testing using instrumented conventional sedans with internal combustion engines because this is what is available. However, both the control concepts and the methods for obtaining consistent performance that we are developing and testing are general ones, and these would be applicable to a wide range of vehicle types powered in various fashions.

In essence, we do not share Mr. Segel's pessimism concerning the reliability of vehicles for future automated highway operation.

The broad questions pertaining to vehicle ownership and the number of vehicle transfers required to make a given trip are complex ones that, when answered, would essentially determine many fundamental characteristics of the resulting system. It seems probable that a more technically efficient system could be developed using nonpersonal vehicles operating in a closed system. However, the final decision as to whether or not to evolve toward highway automation will certainly not be made solely on the basis of such efficiency—an exceedingly important subjective and political factor will certainly be the desire of the individual to own his personal transportation unit. It is difficult to imagine a U.S. Congress that would be willing to legislate substantial restrictions on either the ownership or usage of motor vehicles—especially if the gain were only a slight increase in efficiency. This, in addition to my belief that any automated highway system must evolve in an orderly and progressive fashion from the highways of today, leads me to opt for a system that involves personally owned vehicles.

The vehicle control concepts that we discussed are applicable to intercity highways, and were never intended for general application to intracity highways. With respect to the latter, the problems associated with controlling high-density, multilane traffic with many heavily used entrance and exit points is a task that will probably involve the use of computer facilities that are external to the controlled vehicles.

The question of whether an automated system should be operated asynchronously, semi-synchronously, or synchronously is one that has been debated for a number of years without resolution. Thus far, synchronous systems have been studied under normal flow conditions—generally, steady-state driving in which a vehicle locks onto some type of moving signal—and little effort has been expended on how such a system would handle abnormal situations. Further, little or no effort has apparently been expended on techniques to develop a moving signal for a vehicle to lock on. In short, a wide gap between theory and physical realization presently exists.

It is encouraging to note that the Ford Motor Company has taken an official interest in this approach, and it is hoped that it will sustain this interest by substantial research efforts in this area.

Next, let us consider Mr. Wilkie's comments pertaining to our automatic longitudinal control system. He states that "...steady-state car following is the only problem to which the longitudinal control results reviewed in the paper apply." A careful reading of the paper (or its abstract) shows otherwise, for we have presented results pertaining to lead-car overtaking, steady-state car following, and emergency braking operation. One prime reason for presenting such data was to demonstrate that predictable performance can be obtained under a variety of real-world conditions provided the vehicle is properly instrumented. Such an essential requirement has frequently been overlooked by other investigators. The safe-driving potential of an automatic system characterized by greater reliability, consistent performance, and a lesser reaction time than a human driver certainly implies that a queue of vehicles automatically controlled would be safer than a similar queue of driver-controlled vehicles.

It is appropriate to note that researchers at Ford Motor Company are developing a system that incorporates many of the ideas discussed here—as they have acknowledged in a recent paper (28). In particular, they reported on highway tests of a multimode control system for automatic headway control in a variety of highway situations.

Mr. Wilkie cites one of our recent papers as evidence of the limited theoretical maximum highway capacity of our automatic highway concept. The paper cited deals with an investigation of a particular vehicle control law that was not incorporated into the system discussed here; therefore, the results he cited are simply not applicable to this system. Further, he is concerned that we have not referenced the work of either himself (25) or TRW (24), which deals with synchronous systems for highway automation. Because Mr. Wilkie's paper did not appear in the open literature until January 1971 (although the journal is dated November 1970), some 5 months after our paper was submitted for this meeting, and two weeks after we received his written comments, we are sure that, on reflection, he will see one reason why his paper was not referenced.

Finally, this paper contains a review of progress toward the development of various subsystems for automatically controlling a vehicle on intercity highways; hence, Mr. Wilkie's stated assumption that we intended the paper to be such a review was unnecessary. Further, we must point out in response to his closing comment that most of the experimental data contained herein were collected expressly for this paper and have not been published elsewhere.

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COMPOSITION AND REMOVAL OF AUTOMOBILE WINDSHIELD FILMS

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In an effort to alleviate the problem of impaired visibility caused by automobile windshield films, the origin and nature of the dirt and residues that form windshield films and the most effective methods of removing them were investigated. Samples were collected from windshields and from pavement surfaces, and their composition was determined by infrared spectrophotometry, X-ray diffractometry, and binocular and petrographic microscopy. Cleaning agents and cleaning procedures were evaluated in the laboratory using an automobile windshield. The materials comprising the films are mostly those on or derived from the pavement surface. They consist of organic constituents, which are mainly oil, oxidized oil, rubber, asphalt, and grease. Insect fragments and residues of insect fluids are usually abundant. The inorganic constituents are almost entirely minerals, usually quartz and layered silicates such as mica and clay minerals. As a general rule, the mineral composition of the films reflects the lithology of the aggregates used in the road. Of the commonly used generic types of cleaning agents, the alcohol-detergent type was found to be superior to the predominantly detergent, predominantly alcohol, ammonia, and silicone emulsion types.

WITH today's increasingly motorized society, the problem of impaired visibility caused by windshield films is even more prevalent. In the proposal for this study, Sherwood (9) noted that concern for this problem was expressed by the Virginia State Police. This paper is a result of that concern.

After preliminary investigations, several questions concerning the visibility problem arose. The more important of these questions pertained to (a) the composition of the materials that form windshield and road surface films, (b) the origin and nature of windshield films, (c) the current methods and materials used to clean windshields, and (d) the most effective and efficient methods of removing films from windshields.

PREVIOUS RESEARCH

An extensive search of the literature in the field of driver visibility revealed that very little has been done in this area. Some solvent manufacturers and oil companies have performed intermittent research on windshield film removal, but their findings have never been compiled as formal reports. Whenever possible, these sources were personally contacted for information and advice. The research findings that have been published fall into three general categories: (a) research on road splash patterns and fenders and mudflaps—Giles (6), Forbes (5), Maycock (7), and Anderson and Carlson (3); (b) research on windshield, dash, and wiper characteristics—Sutro (12) and Allen (1); and (c) research in the area of water repellants for aircraft windshields—Thomas (13) and Stedman (10). Most of this work, while interesting as background reading, was inapplicable to the problem investigated (9).

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COMPOSITION STUDIES

Procedures

It was important to know the composition of windshield films in order to study the nature of the materials involved and to evaluate the cleaning agents and methods being used to remove them. Windshield films, especially those formed during the early stages of a rain, appear to originate from two sources: (a) materials splashed up from the roadway, and (b) materials deposited on the windshield from the air or inadvertently placed there by people, i.e., service station attendants.

To study the materials splashed up from the road, pavements were watered down, lightly scrubbed, and the water and any material in suspension were collected. The samples were taken to the laboratory and analyzed by infrared, X-ray, and microscopic methods. Thirteen samples of materials washed from both asphalt and concrete pavements were collected from sampling sites located in the northern, eastern, and central parts of Virginia.

The second type of film-producing material, that already on a windshield before a rain, was also studied. The sample for this investigation was obtained by scraping windshields with a razor blade and collecting the material in a plastic container. This material was similarly analyzed by infrared, X-ray, and microscopic methods. About 50 windshields were scraped; all were located in Charlottesville, Virginia.

The organic content of the samples was determined by infrared analysis. The road scrubbings and windshield scrapings were first leached with carbon tetrachloride, a medium-strength, organic solvent. The leachate was then boiled down to a thick syrup and infrared spectra were obtained. After inspection of the spectra and comparison with known spectra, a semiquantitative organic analysis was obtained for the samples.

Following leaching of the road scrubbings and windshield scrapings for infrared analysis, the remaining particulate matter was allowed to dry and both random and oriented X-ray slides were made of the material; then the mineral constituents were identified by examination of the resulting diffractograms.

Results and Discussion

Before discussing the results of the compositional studies, it should be pointed out that not all variables are considered and that the quantity and composition of windshield films may vary with other factors such as geography, climate, time of the day, season of the year, and type of windshield involved.

Infrared Studies—The leachings and infrared spectra were used to determine the amount and types of organic compounds in the road and windshield samples. It should be stressed that the organic constituents are important because they act as the binder of a windshield film. In most instances the particulate matter in a film would not adhere to the windshield without the organic matter to act as a binder.

The amount of organic matter in the road scrubbings averaged 2.7 percent and the windshield scrapings contained 33 percent organic constituents. The reason for the high percentage of organics in the windshield sample was that many insect remains had been scraped from the windshields. When the insect remains were discounted, the organic compositions of the road scrubbings and windshield scrapings were closely similar. Furthermore, local conditions did not seem to influence the organic composition of film-producing materials.

A summary of the organic compounds found in the samples tested is given in Table 1. It should be pointed out that the undissolved chitin was not identified from infrared spectra but was recognized macroscopically. The major organic fluids found in the specimens were oil and oxidized oil; both probably originated from

TABLE 1

SUMMARY OF THE INFRARED ANALYSIS OF THE ORGANIC CONSTITUENTS OF WINDSHIELD FILM-PRODUCING MATERIALS

Constituent	Probable Common Compound
Undissolved chitin[a]	Insect skeletons
Straight-chained hydrocarbons	Oil
Aromatic groups	Rubber, asphalt
Heavy hydrocarbons	Grease
Complex, unsaturated esters	Insect fluids

[a]Identified macroscopically.

motor vehicles in the form of dripping oil and exhaust fumes. Very small amounts of rubber, asphalt, and grease were also detected. In other studies (4), insoluble soaps have been found in windshield films, but no such compounds were detected in the samples in this investigation.

The amount of organic constituents was greater in the samples washed from asphalt roadways than in those from concrete roadways. The composition of the samples, however, was the same; i.e., the additional organic material was not largely asphalt. These data indicate that asphalt surfaces retain more film-producing materials than do concrete surfaces. A possible explanation for this phenomenon is that asphalt, perhaps more adhesive than concrete, may attract and loosely hold more organics than does the concrete. Alternatively, organics may adhere to organic compounds such as asphalt to a greater degree than to inorganic compounds such as concrete. Therefore, although the concrete may receive as much organic matter as does asphalt, it may be relatively more easily flushed clean (by rain) of the organics than is the asphalt pavement. In any case, only material on the pavement surface would be washed up or splashed up, and the concrete roadways would always yield less film-producing materials than would the asphalt roadways.

X-Ray Diffraction and Microscopic Studies of Composition of Particulate Matter—The central conclusion from these studies, which is presented at the outset because it provides a perspective for the following information, is that the mineral composition of the particulate matter found on windshields very strongly reflects the composition of the stone used as aggregate in the pavement. This implies that there is no particular group of minerals that characterizes windshield films, regardless of geographic location. Rather, the kinds of mineral particles found in the windshield films may change from region to region in response to the type of stone used in the pavements.

However, insofar as there are relatively few minerals that constitute the bulk of the rocks commonly quarried for use as aggregate (sandstone, limestone, granite, basalt, etc.), the species of minerals in windshield dirt are in general limited and are usually feldspar, quartz, micas, amphiboles, pyroxenes, carbonates, and clays. Those that are ubiquitous in nature—e.g., quartz and clay—are also more widely encountered in windshield material.

X-Ray Studies—A summary of the mineral constituents found in the samples washed from pavements is given in Table 2. When X-ray intensity was considered as a measure of volume as opposed to presence of a particular diffraction peak in the samples, it was found that the main minerals in the road scrubbings were illite-mica and quartz. Lesser amounts of expandable clay, feldspar, kaolinite, and calcite were also present. The windshield scrapings contained quartz, illite-mica, and feldspar.

With the exception of calcite, these findings were expected because the minerals identified are among the ones most commonly found in nature. Calcite, which is somewhat soluble under natural conditions, might not be expected in such abundance. It was found, however, that the calcite occurred only in samples washed from pavements constructed with calcite-bearing aggregate. The calcite powder had obviously been washed from the exposed surfaces of the aggregate.

Microscopic Studies—Microscopic studies were performed only on samples collected from windshields. The two types of samples were as follows:

1. Material deposited on and subsequently scraped from 4- by 5-in. glass plates mounted on the windshields of State Police cars stationed in Charlottesville and Lynchburg, and Highway Department vehicles stationed in Charlottesville and Staunton. The plates were allowed to remain on the windshields for periods of two to eight months, during which time they were not cleaned and were simply allowed to collect the normal accumulation of windshield deposits.

TABLE 2

SUMMARY OF X-RAY ANALYSES OF THE MINERAL CONSTITUENTS IDENTIFIED IN THE SAMPLES WASHED FROM PAVEMENTS

Mineral	Percent of 13 Samples in Which Present	Mineral	Percent of 13 Samples in Which Present
Quartz	100	Feldspar	70
Illite-mica	100	Kaolinite	55
Expandable clay	70	Calcite	40

2. Material collected from automobiles in the Charlottesville area by scraping windshields in the University of Virginia and public parking lots. The material from 50 cars was combined and constituted the sample.

Both types of samples were leached with CCl_4 to dissolve the organic material and to separate the light and heavy fractions. The particulate matter was then separated into size fractions by sieving, and a portion of each fraction taken for a fragment mount in liquids of the appropriate refractive index.

The results of the flotation and sieving of sample 2 are given in Table 3.

There was no observable mineral matter in the lightweight fractions. All three lightweight fractions appeared to be composed exclusively of biologically derived material with little difference between the materials except size. In the coarsest material (+40 mesh) all the material appeared to be insect or plant fragments, spore cases, pollen, seeds, and exoskeletons.

The fraction passing the No. 40 and retained on the No. 100 (-40+100) had the same composition as the +40—smaller fragments of the same things. There were, however, more hairs and fibers and discrete pollen (?) particles. The finest (-100) fraction contained the same type of material as the -40+100 fraction.

The heavy fractions were composed largely of mineral matter with some exceptions. The coarsest material (+40) was composed of apparently lithic fragments ($\cong$ 0.5 to 1.5 mm), which in turn were aggregates of smaller ($\cong$ 0.01 to 0.07 mm) mineral grains.

The -40+100 fractions were composed mostly of particles with the aggregate structure described. There were some individual mineral grains present, mostly of quartz; others in order of abundance were calcite, mica, and feldspar.

The finest (-100) fraction contained almost entirely tiny individual grains of minerals, with some small aggregates and clusters as described earlier. Particle shapes were mostly equidimensional and varied from angular to subrounded. There were numerous elongated lath-shaped fragments. The fraction, in order of abundance, was composed of micas (chlorite and biotite), quartz, calcite, feldspar (microcline and plagioclase), and epidote.

In each of the size fractions of the heavy material there was a small amount of extraneous material in the form of hairs, fibers, chitin, and spores, similar to the material on the lightweight fraction.

Most stone used in portland cement and bituminous concrete in the Charlottesville area is supplied by two local quarries; the first is in the Catoctin greenstone, which is a dense meta-basalt composed essentially of chlorite, hornblende, epidote, feldspar, quartz, calcite, and tremolite; the second quarry is in the Lovingston (granite) gneiss, which is composed essentially of feldspar, quartz, and biotite, and has appreciable amounts of other minerals including calcite and epidote.

It is apparent that the suite of minerals comprising the rocks quarried in the Charlottesville area are well represented in the dirt accumulating on automobile windshields there. Thus, from the results of the microscopic and X-ray diffraction analyses one may establish the principle that the mineralogical component of windshield films derives from the accumulation on the windshield of the products of normal attrition and abrasion of the stone of which the pavement is composed.

It should also be observed that an additional geological principle may be operating here. The end products of weathering of essentially all silicate rocks, regardless of their original mineralogy, are quartz and clay. Other products from these and other types of rocks (e.g., carbonates) are materials in solution and not of concern here. Thus, if the first-generation fragments of a given pavement are fine-grained enough and the pavement of sufficient age, one may find to some extent in windshield dirt the normal

TABLE 3

SIEVE SIZE ANALYSIS OF LIGHT AND HEAVY FRACTIONS OF SCRAPED WINDSHIELD MATERIAL

Sieve Size	Weight Percent	
	Heavy Fraction[a]	Light Fraction[a]
+40	2.44	26.5
-40+100	38.3	38.3
-100	57.0	31.0
Loss	2.47	4.45

[a]Proportions of total sample of light and heavy fractions were 25 and 75 percent respectively.

end products of weathering (that is, clay and fine-grained quartz) regardless of the original lithology of the stone in the pavement.

The recognition that the particulate matter in windshield dirt may be largely mineral raises the question of the possibility of the abrasion and scratching of windshields during the cleaning or auto-wiping procedure when the accumulated dirt being removed is derived from pavements constructed of stone whose mineral components are harder than glass.

Allen (2) concluded that micro-scratches and abrasion of windshields caused by windshield wiper action or cleaning can be sufficient to impair the windshield. His results are summarized as follows: Thirteen used windshields were randomly selected for test. Code monograms on each indicated they probably were the original-equipment windshields. Photographs were made of the scattered light surrounding automobile headlights viewed through the windshields. Damage from windshield wiper action seemed to be related to miles of travel. Damage from cleaning and ice-scraping operations was unrelated to age in this small sample. Pitting from small high-velocity particles also appeared. On a subjective rating scale, 8 of the 13 windshields were judged to be damaged enough to cause a noticeable increase in glare, especially at night, and to warrant consideration of replacement with a new windshield. Four were judged to be unsafe for night driving.

Most of the common rock-forming minerals will scratch glass; these include quartz, feldspar, amphibole, pyroxene, olivine, and some of the iron oxide minerals. Other iron oxide minerals, the carbonates (calcite and dolomite) and the micas and clays will not scratch glass.

The implications of this information are clear; most of the time, most motorists will be driving with dust or dirt on their windshields that is capable of scratching the glass. It is conceivable that automobiles being driven exclusively within, for example, areas of limestone terrane (over bituminous surfaced roads as opposed to portland cement concrete, which would contain sand) may be relatively free of abrasive dust. In general, the precaution of flushing the windshield before any wiping procedure should be taken. It is realized that flushing is only convenient before cleaning from the outside, and that it cannot effectively be done using the windshield washers when traveling on the highway. Another procedure that should be followed routinely is to wipe the wiper blades free of any adhering particles.

SERVICE STATION SURVEY

Procedure

To ascertain what cleaning implements and agents were currently being employed in removing automobile windshield films, a poll of service stations in central Virginia was conducted. The types of data collected included the name of station and its location; the oil company; the situation (rural, suburban, urban); the station size (number of islands); the type of windshield solvent used; and the type of wiping implement used.

Results and Discussion

Two hundred and eighteen service stations, representing 21 oil companies, were canvassed. The stations were located as follows: Richmond (60 stations), Charlottesville (58 stations), Harrisonburg (26 stations), Staunton (26 stations), Waynesboro (26 stations), and various rural locales (22 stations). Sixty-seven percent of the stations were in urban areas, 23 percent in suburban areas, and 10 percent in rural areas. The size of the stations ranged from one to four gas pump islands; 51 percent were one-island stations, 45 percent were two-island stations, and 3.5 percent were three-island stations.

The stations polled used 36 different cleaning agents (Table 4). Actually, the number of solvents in use may not be so great because one solvent manufacturer often supplies many companies, which have different brand names for the same cleaner.

It is interesting to note that water was by far the most commonly used solvent. As is shown in the section on cleaner evaluations, water was the poorest cleaner tested.

TABLE 4

CLEANING AGENTS USED BY SERVICE STATIONS IN CENTRAL VIRGINIA

Cleaning Agent	No. of Stations	Percentage of Station Total (218)	Cleaning Agent	No. of Stations	Percentage of Station Total (218)
Water	55	25.2	Durkee-Atwood glass cleaner	4	1.8
Ammonia and water	25	11.5	Mobil 101 concentrate	4	1.8
Detergent towels[a]	25	11.5	G. M. windshield concentrate	3	1.4
Trico solvent	23	10.5	Gulf Klear-Shield	3	1.4
DuPont glass cleaner	14	6.4	Household detergent	3	1.4
Atlas Glass-Kleen	10	4.6	Phillips 66 glass cleaner	3	1.4
Car wash soap	7	3.2	Scott glass cleaner	3	1.4
Windex glass cleaner	7	3.2	Skyline glass cleaner	2	0.9
Bon Ami liquid	5	2.3	17 others	17	7.7
Shell windshield concentrate	5	2.3	Unknown	1	0.5
Windex with ammonia glass cleaner	5	2.3			

[a]A type of two-layer paper towel; one layer, impregnated with detergent, is used for cleaning, and the reverse side is used for wiping and drying.

Eighteen of the stations using water added a commercial solvent as an antifreeze agent during the winter months and, as a result, probably afforded better windshield service at that time of the year. The popularity of water at service stations is undoubtedly due to its convenience and economy.

Cleaning implements used at the stations are given in Table 5. The total percentage is greater than 100 because many stations used more than one type of cleaning implement. Most of the stations made an effort to use a good cleaning implement such as paper towels; unfortunately, at the same time they used inferior solvents such as water or ammonia and water.

Service station attendants were generally apathetic on the subject of windshield cleaning. It was noted also that, through either lack of training or negligence, attendants often themselves contributed to windshield film. Attendants often sprayed their solvents in one spot and then did not wipe the windshield dry. The result was a partially cleaned windshield and a dried soap film. In other instances, attendants were seen wiping the crankcase dipstick on a paper towel or rag and then using this same paper towel or rag to "clean" the windshield. A thin oil film was left on the windshield. By other, less obvious, means, attendants may leave oily films on windshields; e.g., through continuous turning of paper towels while wiping the glass, they deposit oil picked up from their hands onto the windshield. Even if the attendants' hands are clean, there are enough fatty acids in the skin to be transmitted to the paper towel, and these fats are then rubbed onto the glass, creating a film (8).

Another shortcoming with most windshield service is the failure to clean the wiper blades. No matter how clean a windshield is, one swipe with dirty blades will leave an obscuring film.

In all fairness, it should be pointed out that the indifference of attendants is not always the cause of poor windshield service. Lack of training also appears to be a contributing factor. Some oil companies are now initiating dealer training programs in an attempt to provide better service to motorists, but the job is far from complete.

TABLE 5

CLEANING IMPLEMENTS USED BY SERVICE STATIONS IN CENTRAL VIRGINIA

Cleaning Implement	No. of Stations	Percentage of Station Total (218)
Paper towels	145	66.5
Bug sponge	53	24.3
Detergent towels	25	11.5
Clean cloth rags	23	10.5
Dirty cloth rags	15	6.9
Sponges	9	4.1
Bug brushes	3	1.4
Chamois	1	0.5

CLEANING IMPLEMENT AND CLEANING AGENT EVALUATIONS

Procedures

To evaluate the efficiency of the commonly used cleaning implements and agents as determined from the service station survey, and some other randomly chosen ones, a controlled laboratory experiment was devised. An automobile windshield was obtained, mounted on an eye-level frame, equipped with vacuum wipers, and divided into four sections with vertical strips of black tape on the inside of the glass (Fig. 1).

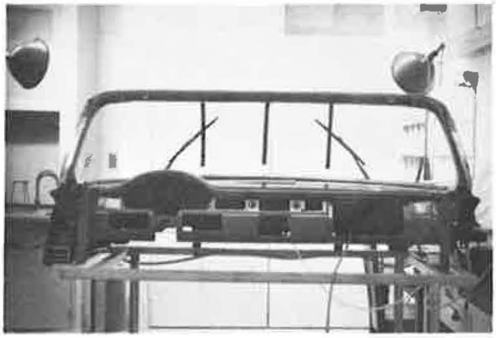

Figure 1. Apparatus used in evaluations of windshield cleaning implements and cleaning agents.

Three sections of the windshield were smeared with a mixture of used crankcase oil and a fine-grained soil rich in clay, quartz, and mica. This mixture approximated the composition of an ordinary windshield film except that the amount of organic material was higher. The fourth section of the windshield was cleaned with a laboratory glass cleaner and was used as a standard for "cleanness." Cleaning implements and cleaning agents were tested separately. The soiled sections of the windshield were first cleaned with water and various cleaning implements and the sections rated for cleanness. Following each test the windshield was thoroughly cleaned with laboratory glass cleaner and dried; then various solvents were used after the sections had been smeared again with the oily mixture. This time only paper towels were used for wiping. After wiping dry, a fine mist of water was sprayed on each of the four sections. If the previously soiled sections of the windshield ran free of water as did the standard clean section, they were rated as clean. If not, the degree of "beading-up" (taken as an indicator of film residue) was rated. The ratings were made by a panel of five people who did not know what implements or solvents had been used. These people were of varied backgrounds and education, and the panel was not always composed of the same persons. Tests were repeated to check for reproducibility of results.

It is realized that this testing technique is biased toward those cleaners containing wetting agents, but it is also realized that these agents aid in obtaining a clear, film-free windshield.

Results and Discussion

The technique for evaluating cleaning implements and solvents proved fairly successful and results were generally reproducible. In no case were the judges in radical disagreement; some might rate a solvent as good and others as very good, but the instance of some rating it good and others poor did not occur.

Cleaning Implements—Four types of cleaning implements were tested: (a) detergent towels, (b) ordinary paper towels, (c) rags, and (d) sponges. The four were rated for their film-removing ability in the order given.

Figure 2 shows that all four cleaning implements removed some of the film, but only the detergent towel provided a good cleaning job. In fact, the detergent towel section appeared as film-free as the standard clean section of the windshield. The excellence of the detergent towel was undoubtedly related to the fact that it contained chemicals capable of dissolving the oily film. Only water was available as a solvent with the other implements, and the result was a poorly cleaned windshield.

The sponge yielded the worst cleaning job because it smeared the oil on the glass; also, the windshield could not be thoroughly dried with this moist material.

The rag appeared to have removed almost as much of the oil from the glass as had the ordinary paper towel. Windshields cleaned with both, however, showed beading of the water, and obviously the windshield had not actually been cleaned. Also, it should be pointed out that the rag tested had been freshly laundered, which is not always the case at service stations. It has been shown, however, that even freshly laundered rags often contain soapy calcium and magnesium stearates. When windshields are wiped with these rags, the stearates are deposited on the glass. During a rain, troublesome, smeared films are then formed (4).

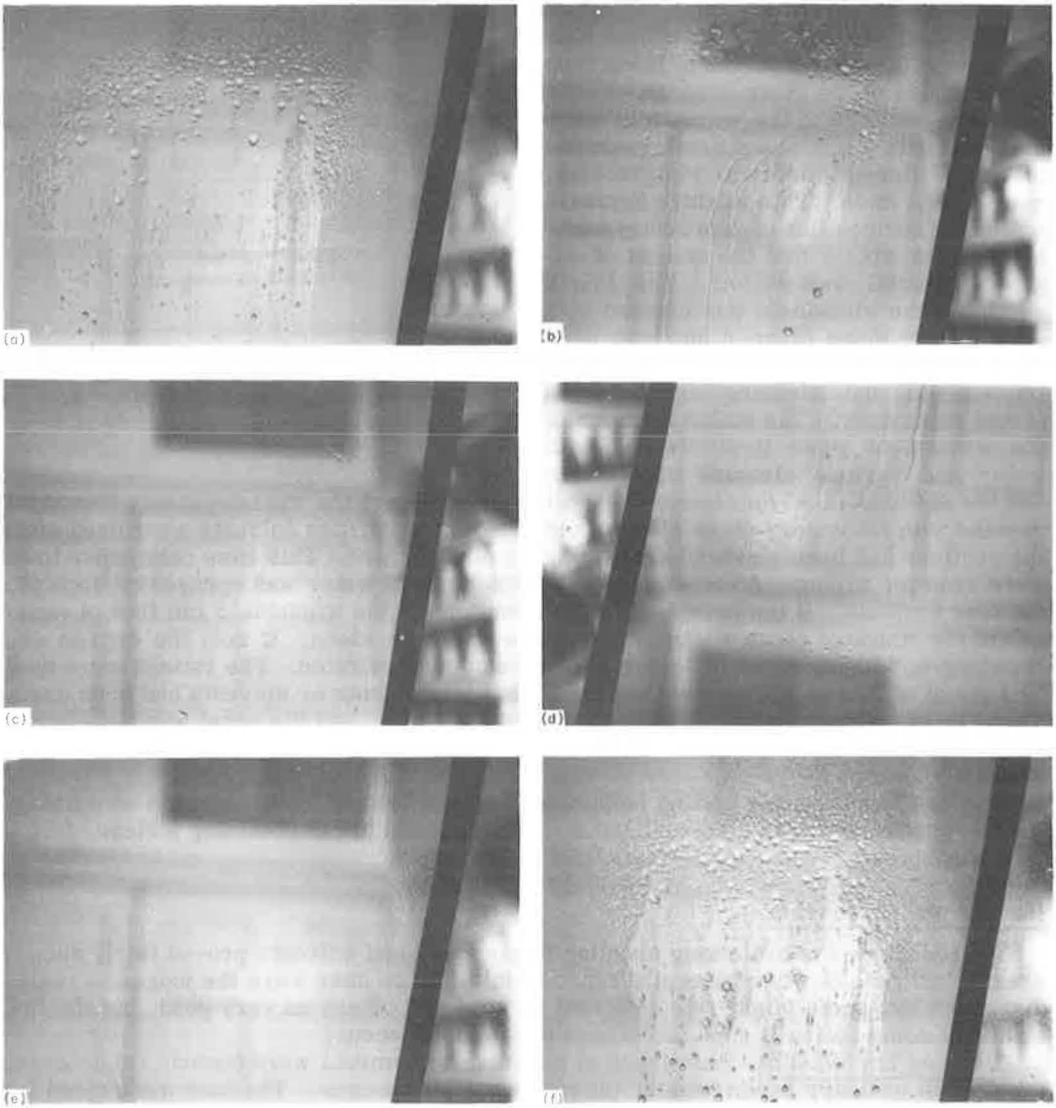

Figure 2. Sections of windshield after being cleaned with various implements and then sprayed with a fine mist of water: (a) rag cleaned, (b) paper towel cleaned, (c) sponge cleaned, (d) detergent towel cleaned, (e) standard clean section, and (f) uncleaned.

Because rags are very porous, their use for cleaning glass is even more undesirable. Film-producing, fatty acids from an attendant's hands are easily transmitted through the cloth onto the windshield. The resultant film causes diminished visibility in rain or glaring light (8).

Cleaning Agents—Seven types of cleaning agents were tested in the experiments: detergent towel, alcohol-detergent type, predominantly detergent type, predominantly alcohol type, ammonia type, silicone emulsion type, and water. All of these, except water, have some capacity to dissolve the oily organic constituents of a windshield film. One type of cleaner in fairly common use, the abrasive type, was not tested.

Photographic comparisons of the tests are shown in Figure 3, and a summary of test evaluations is given in Table 6. It should be realized that these evaluations do not imply

Figure 3. Sections of windshield after being cleaned with various solvents, wiped dry with paper towels (detergent towel provided its own wiping material), and sprayed with a fine mist of water: (a) cleaned with alcohol-detergent type, (b) cleaned with detergent towel, (c) cleaned with predominantly detergent type, (d) cleaned with predominantly alcohol type, (e) cleaned with ammonia type, (f) cleaned with silicone emulsion type, (g) standard clean section, and (h) cleaned with water.

that the poorer rated solvents are not useful for purposes other than windshield cleaning. One should also keep in mind that these evaluations are based entirely on one particular testing method.

TABLE 6

SUMMARY OF EFFECTIVENESS OF CLEANING AGENTS

Agent	Rating
1. Alcohol-detergent type	Very good
2. Detergent towel	Very good
3. Predominantly detergent type	Good
4. Predominantly alcohol type	Good
5. Ammonia type	Fair
6. Silicone emulsion type	Poor
7. Water	Very poor

The alcohol-detergent type solvent cleaned as well as the laboratory glass cleaner, and the detergent towel used with water performed almost as well. Water did not bead on the glass after cleaning but flowed freely as it did on the standard clean section of the windshield.

The predominantly detergent and predominantly alcohol types of cleaners performed almost as well as the alcohol-detergent type and the detergent towel. Only slight beading on the glass was noticed after cleaning.

Ammonia types of cleaners did only a fair job of cleaning the windshield film. This situation was perhaps caused by the lack of a wetting agent in the solvents. A point worth mentioning is that ammonia should not be used in high concentrations because it may cause discoloration of paint and corrosion of metals.

The silicone emulsions tested did an obviously poor job of cleaning. They were rated as slightly better than water, but the difference between the two was often difficult to distinguish. A further disadvantage of these cleaners is that they cannot be used in windshield washers because of the high pressure needed to dispense them. There is, however, one notable benefit that accrues from use of cleaners containing silicone emulsions—they can be used as temporary protection against fogging (11).

After evaluation of the cleaners, the question of solvent performance in windshield washers arose, and as a supplementary experiment the better cleaners were selected and sprayed simultaneously with water onto the soiled windshield. The wipers were kept in operation. This experiment approached the circumstances surrounding a splash type of film during the early stages of a rain. It was found that the cleaners worked well in the spot where they hit the windshield, but the solvents did not spread and clean the entire glass. The wipers, surprisingly, did not aid in spreading the cleaners but simply swept the cleaners to the edge of the windshield, where they drained off. It was then postulated that under actual conditions the wind induced by a moving automobile might provide better spreading of the solvent. In a test with an automobile, the same situation of one-spot cleaning prevailed, but only temporarily. It was found that if large amounts of the solvent were repeatedly sprayed on with the washers the entire windshield could be cleaned.

SUMMARY

The major results and conclusions are as follows:

1. The materials producing windshield films during the early stages of a rain appear to be either those splashed up from the road surface or those already on the windshield, deposited there from the environment or inadvertently placed there by people.

2. Of the materials splashed up from the road surface, 2.7 percent is composed of organic constituents. These constituents, as analyzed by infrared spectrophotometry, are primarily oil and oxidized oil with very small amounts of rubber, asphalt, and grease.

3. Of the materials deposited on the windshield from the air or placed there by man, 33 percent is composed of organic constituents. These constituents also contain oil, oxidized oil, rubber, asphalt, and grease, but very large amounts of insect remains are also present.

4. The main mineral constituents of both types of film-producing materials are quartz and layered silicates such as mica and clay minerals. Minor mineral constituents are feldspar and calcite.

5. Geographic location does not seem to affect the organic composition of film-producing materials but does affect the mineral composition of these materials; the

mineral composition apparently reflects the lithology of the particular aggregates used in the road.

6. The organic constituents appear to act as the binder of windshield films, holding the particulate matter together and adhering to the glass of the windshield.

7. The amount of organic matter on asphalt road surfaces is greater than that on concrete road surfaces, but the organic composition is the same.

8. The most commonly used cleaning agents at service stations in central Virginia are water, ammonia, detergent towels, and Trico solvent; and the most commonly used cleaning implements are paper towels, bug sponges, detergent towels, and rags.

9. Service stations tend to use good cleaning implements but poor cleaning agents.

10. Service station attendants polled in the survey were generally apathetic concerning the subject of windshield service and often were observed using poor cleaning methods such as touching the windshield, using dirty towels or rags for wiping, spraying a solvent in only one spot, or failing to clean the wiper blades.

11. The only cleaning implement found to do a respectable job when used with water alone was the detergent towel.

12. Test results of commonly used types of cleaning agents revealed the following ratings: very good, alcohol-detergent type and detergent towel; good, predominantly detergent type and predominantly alcohol type; fair, ammonia type; poor, silicone emulsion type; and very poor, water.

13. In automobile windshield washer experiments, it was found that solvents cleaned only in the spot that they hit unless very large amounts of the solvents were used.

RECOMMENDATIONS

As a result of this study, the following recommendations are made. Note that many of these recommendations deal with films formed during the early stages of a rain, but others are given because they pertain to windshield service in general.

1. It is recommended that service stations use an alcohol or alcohol-detergent type of windshield solvent and that detergent towels be used for wiping. If detergent towels are not used, clean paper towels should be used. Sponges and rags are not recommended for wiping. A bug sponge or other light abrasive material should be kept on hand for loosening stubborn windshield deposits such as tar, paint, or insects.

2. Service station attendants, either through training programs or in some other way, should be advised in proper windshield cleaning methods. It is recommended that the section of the windshield to be cleaned should first be flushed with a heavy stream of water and then sprayed all over with a fine mist of the solvent (not in just one spot), that clean paper towels or detergent towels be used for wiping without excessive turning of the towel, that the windshield should be thoroughly dried with the towel, and that the wiper blades should be cleaned. Such practices as using rags, or soiled paper towels, or touching the windshield with the hands should be discouraged.

3. Windshield washer reservoirs should be filled with a solvent other than water. Any of the alcohol or detergent types of commercial cleaners are recommended. An acceptable all-weather solvent can be made easily by mixing 4 parts methanol (wood alcohol) or isopropanol (rubbing alcohol), approximately 1 part household liquid detergent, and 5 parts water. Note that the proportion of detergent suggested is approximate. Viscous and more concentrated detergents should only be $\frac{1}{4}$ to $\frac{1}{2}$ part to avoid foaming or bubbling of the mixture when it is sprayed on the windshield.

4. In the early stages of a rain, when splash films appear on the windshield, motorists are advised to turn on their wipers and to pump large amounts of solvent through their windshield washers. In the experiments involved in this study, this wiping and washing exercise eliminated the worst of films.

5. It is recommended that windshield washer nozzles be designed to spray across the entire windshield instead of in just one or two spots. This arrangement would allow the entire windshield to be quickly and effectively cleaned.

6. Wipers should be run at slow speed except during very heavy rainfall. The wipers give better service at this speed because they are in closer contact with the windshield.

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A THREE-DIMENSIONAL MATHEMATICAL MODEL TO PREDICT THE DYNAMIC RESPONSE OF AN AUTOMOBILE OCCUPANT

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This paper outlines the development of an analytical model that predicts the response of an automobile passenger in three-dimensional space during vehicle motion, which can also be three-dimensional in nature. The predicted response includes position of the occupant relative to the vehicle, accelerations of various parts of the body, and forces acting on various parts of the body—all as a function of time.

Validation of this passenger model has been achieved for the case of frontal collisions in which the occupant is either totally unrestrained, restrained by a lap belt only, or restrained by a lap belt and a shoulder strap.

•ENGINEERS are currently attempting to reduce the severity of single vehicle accidents by designing and building a safer roadway environment.

To effectively design or evaluate a roadway or its immediate environment for safety, consideration must be given to the dynamic response of the vehicle and occupant during interaction with geometric features such as curves and ditches, or obstacles such as guardrails, bridge rails, median barriers, and signposts. Accordingly, the design of highway safety devices such as breakaway signs, energy-absorbing impact cushions, and earth berms (an earth embankment geometrically designed to safely redirect a vehicle that has left the roadway), depends directly on the dynamic response of vehicle and passenger during collision with these objects.

These considerations are accurately summarized in the following quotation (1):

> Unless the motion time history of the vehicle can be translated into the expected kinematics of the vehicle occupant and further translated into the nature and extent of physical damage, it is not possible to establish performance requirements for roadside structure modifications that will effect a reduction in occupant injuries during single vehicle collisions.

The reported research was aimed at providing an analytical means of supplementing existing technology as related to roadside energy conversion systems. This was accomplished by developing a mathematical model to predict the response of an automobile passenger during violent vehicle motion of a general nature, i.e., a three-dimensional path including simultaneous rotations about the three directions.

DESIGN CONSIDERATIONS

Usual design practice is to first determine the time history and levels of acceleration (g-levels) experienced by the vehicle during a particular maneuver or collision. These are next compared to certain tolerance limits assuming that the occupant is subjected to the same g-level. This assumption is rigorously true only if the occupant is rigidly fastened to the vehicle. In actuality the passenger is unrestrained, lap-belted,

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or shoulder-harnessed and movement is not completely restricted, so that this assumption could range anywhere from overly conservative to dangerously inadequate depending on the situation.

Another factor that influences highway safety design problems is the quantitative consideration of contact forces between vehicle occupant and vehicle interior. It is possible for an automobile passenger to suffer fatal injuries from contact forces during a vehicle maneuver that at present may appear completely tolerable from the standpoint of vehicle accelerations alone.

It is felt that an analytical model of a passenger used in conjunction with available biomechanics data on human tolerance limits can be of significant value in approaching highway safety design problems.

REVIEW OF LITERATURE

A survey of the literature has shown that the mathematical modeling of a vehicle occupant has been attempted in recent years. In most cases these efforts were aimed at developing restraint systems for the occupant, but in no instance was the occupant's general dynamic response the prime consideration.

In the early 1960's, a mathematical approach to the occupant restraint problem was made by the aerospace industry (5, 10). The primary concern was the behavior of viscera for fully restrained subjects.

During 1962-63, an analytical study of occupant restraint systems was performed by Cornell Aeronautical Laboratory (CAL) (7). A 7 degree-of-freedom nonlinear mathemathical model of a restrained, articulated body on a test cart, for the case of a frontal collision, was formulated and programmed for an electronic computer. This study also led to the development of an 11 degree-of-freedom passenger model completed in 1966, which is the most sophisticated yet employed in the occupant restraint problem (9).

In 1967, Emori (2) conducted a study whose purpose was "to understand the mechanics of the automobile collision and to establish a logical background for the injury reduction of occupants." The scope of his research precluded the use of the CAL model and a single degree-of-freedom spring mass system for the occupant, and a similar representation of the automobile was used.

Renneker (11) used a 2 degree-of-freedom model of an occupant characterized by hip and torso restraint to study the effect of vehicle forestructure energy absorption on occupany injury.

Martinez and Garcia (6), in 1968, developed a mathematical model to represent the motion of the head and neck during rear-end collisions to study the whiplash phenomenon.

In 1969, Suggs et al. (12) considered the problem of objectionable amplitudes and frequencies in the vibration of seats using a 2 degree-of-freedom representation of the human for the purpose of developing more comfortable seats.

With the exception of the CAL model (9), the foregoing efforts have little in common with the reported research but are acknowledged because they were mathematical simulations of the vehicle occupant.

The CAL model provided the major guidelines for performing this research because, in this writer's opinion, the results of that study reflect an adequate representation of the vehicle occupant for the two-dimensional environment considered. However, the specific equations derived by CAL were not applicable to this study because this study involves a three-dimensional formulation, although the same basic geometrical configuration and concepts were applicable.

MATHEMATICAL FORMULATION

Vehicle Occupant

The vehicle occupant is defined separately from the vehicle, or as an independent system of articulated rigid mass segments in three-dimensional space. Consequently, the vehicle interior can be thought of as a confining environment for the occupant and is discussed in a subsequent section.

Figure 1 shows the centerlines of the 12 rigid mass segments and their connection pattern, chosen as to geometrically resemble the human body. Fixed at the center of mass of each segment n is a right-handed cartesian coordinate system denoted by axes X_n, Y_n, and Z_n. The positive directions of these axes are defined such that when the body is standing upright with arms hanging vertically (downward) X_n will be positive straight ahead, Y_n will be positive to its left, and Z_n will be positive upwards. The orientation of segment n with respect to the space-fixed coordinate system denoted by axes X', Y', and Z' is defined using three angular coordinates commonly referred to as "Eulerian angles" (4).

If all joints of the articulated body shown in Figure 1 were of the ball-and-socket type, then this body would have 39 degrees of freedom, i.e., 36 angular coordinates (3 Eulerian angles for each of the 12 rigid mass segments), plus the 3 translational coordinates $(X'_{T1}, Y'_{T1}, Z'_{T1})$ for the reference point on the body. [Such a point is

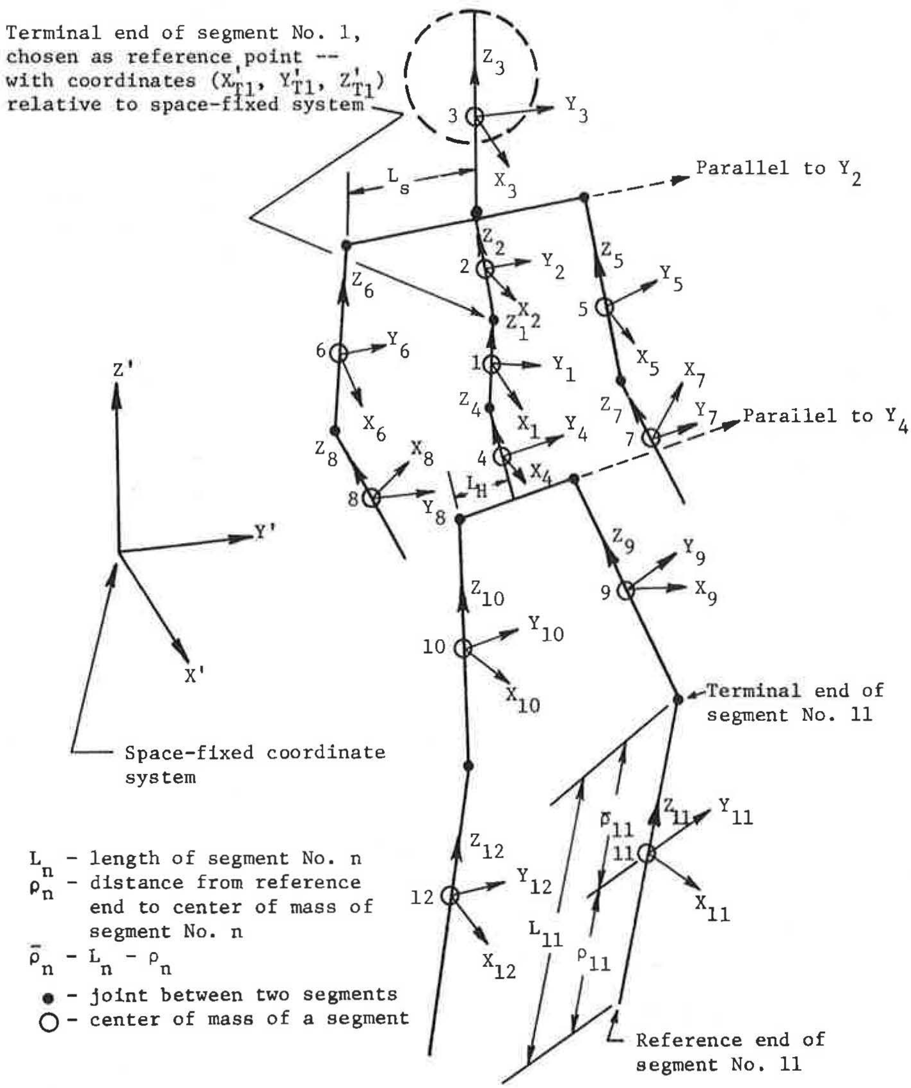

Figure. 1. Articulated body with coordinate systems.

needed to account for translation of the body as a unit (Fig. 1).] However, it was realized that the elbows and knees are pinned in nature; therefore only 1 angular coordinate is required (instead of 3) to specify the orientation of a forearm or a lower leg segment in space. Consequently, the vehicle occupant has 31 degrees of freedom that also correspond to the 31 generalized coordinates used in Lagrange's equations (4) to derive equations of motion for the articulated body.

Lagrange's equations for nonconservative systems (4) were employed, and these may be written as

$$\frac{d}{dt}\left(\frac{\partial U}{\partial \dot{q}_j}\right) - \frac{\partial U}{\partial q_j} + \frac{\partial V}{\partial q_j} = Q_j \tag{1}$$

where t = time, U = kinetic energy of the system, V = potential energy of the system, q_j = generalized coordinates, $\dot{q}_j$ = generalized velocities, Q_j = generalized forces acting on the system that are not necessarily derivable from a potential function, and j = 1, 2, ..., 31, for this particular problem.

The potential energy, V, is of two types; i.e., potential energy of position (due to gravity) and potential energy due to restoring springs located in each of the two back joints shown in Figure 1. These rotational springs simulate spinal elasticity or the ability of the human spine to recover its initial configuration after bending.

The generalized forces, Q_j, are also of two types; i.e., generalized forces resulting from externally applied loads (passenger-vehicle interaction) and generalized forces resulting from frictional resistance in all joints (viscous damping) to simulate muscle tone. The human body's muscular network can act as a dissipater of rotational kinetic energy that is derived from an external source. Hence, the viscous damping in body joints approximates the tensing of muscles in a panic situation.

Passenger-Vehicle Interaction

The idea of passenger-vehicle interaction is analogous to that of placing an object in a glass box, fastening the lid, and then observing the motion of the object while the box is shaken. One could conclude from such an experiment that the motion of the object is totally dependent on the forces afforded to it by the walls of the box (with the exception of gravity), and that these forces are dependent on the path of the box in space as a function of time. Likewise, before contact forces on the passenger can be computed, it is necessary to define the path of the vehicle.

A tabular record of the vehicle's path in space as a function of time is sufficient for purposes of computing contact forces. This record is fed to the computer program for the passenger model and, if necessary, interpolation between time stations is performed. A record of the vehicle's path can be obtained from another computer program that describes vehicle motion (8, 13) or from full-scale testing.

The Idealized Passenger Compartment—To facilitate the computation of contact forces, the vehicle interior or passenger compartment is idealized by a series of planar surfaces. This greatly simplifies the geometry considerations for predicting contact between the articulated body and its confining environment.

Figure 2 shows the numbering of the points where coordinates are necessary for defining the geometry of the idealized passenger compartment. These points are used to express the equations of the planar surfaces and their inward normal vectors.

The Prediction of Contact—The computer program is written such that the passenger is initially placed inside the vehicle; then each of the various parts of the articulated body are checked for contact with each of the planar surfaces of the vehicle interior as the vehicle moves along its path. The technique used to predict contact employs the use of spheres and lines as well as the planes that define the vehicle interior. A finite number of spheres are strategically located along the segments of the articulated body (Fig. 3) for the purpose of giving size and dimension to the body segments. The proximity of each "contact sphere" to each planar surface of the passenger compartment is calculated by (a) passing a line through the center of the sphere in a direction parallel to the inward normal vector of the planar surface; (b) finding the point of intersection

(X_{vi}, Z_{vi}) - coordinate of point i in X_v - Z_v plane

Note: $Z_{v5} = Z_{v18}$; $Z_{v20} = Z_{v21}$; $Z_{v6} = Z_{v11} = Z_{v19}$.

$Z_{v2} = Z_{v3}$; $Z_{v17} = Z_{v8} = Z_{v13} = Z_{v14}$; $X_{v11} = X_{v12} = X_{v15}$;

$X_{v6} = X_{v7} = X_{v22}$.

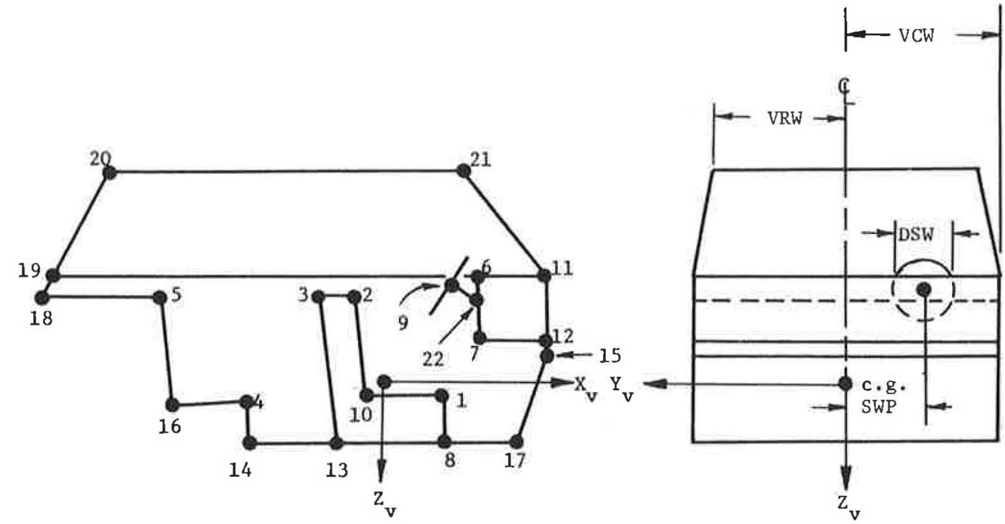

Figure 2. Coordinates and dimensions of the idealized passenger compartment.

of the line with the plane; and (c) calculating the distance between this point of intersection and the center of the contact sphere. Contact or amount of deformation is computed by comparing the radius of the sphere to the distance of its center from the planar surface (item c). Finally, the contact force is computed based on force-deformation data that are input to the computer program.

Lap and Torso Restraint Belts—Other sources of contact forces that the vehicle occupant may be subjected to are the safety belts. The lap belt has its ends anchored at arbitrary points and loops around the pelvic area (contact sphere No. 3). Likewise, the torso belt has its ends anchored at arbitrary points and loops around the upper torso area (contact sphere No. 2).

It is assumed that the centerline of a belt defines a plane that contains the center of its respective contact sphere at all times. This facilitates the definition of the restraining force vector, which by definition also lies in this plane.

Solution of Equations

The equations of motion derived from Eq. 1 comprise a set of 31 differential equations that are categorized as being ordinary, of second order, simultaneous, and nonlinear.

The fact that these differential equations are nonlinear immediately dictates a solution by numerical integration, and the particular approach used was the "Runge-Kutta" method (3) because of its inherent stability. Differential equations to which this method is applicable must be of the form where the highest derivative is expressible as a function of lower derivatives, the dependent variable, and the independent variable. For this reason the 31 differential equations of motion were written in matrix form as

$$[D] \{\ddot{q}\} = \{\overline{E}\} \tag{2}$$

from which the column vector of highest derivatives $\{\ddot{q}\}$ is available for integration with respect to time.

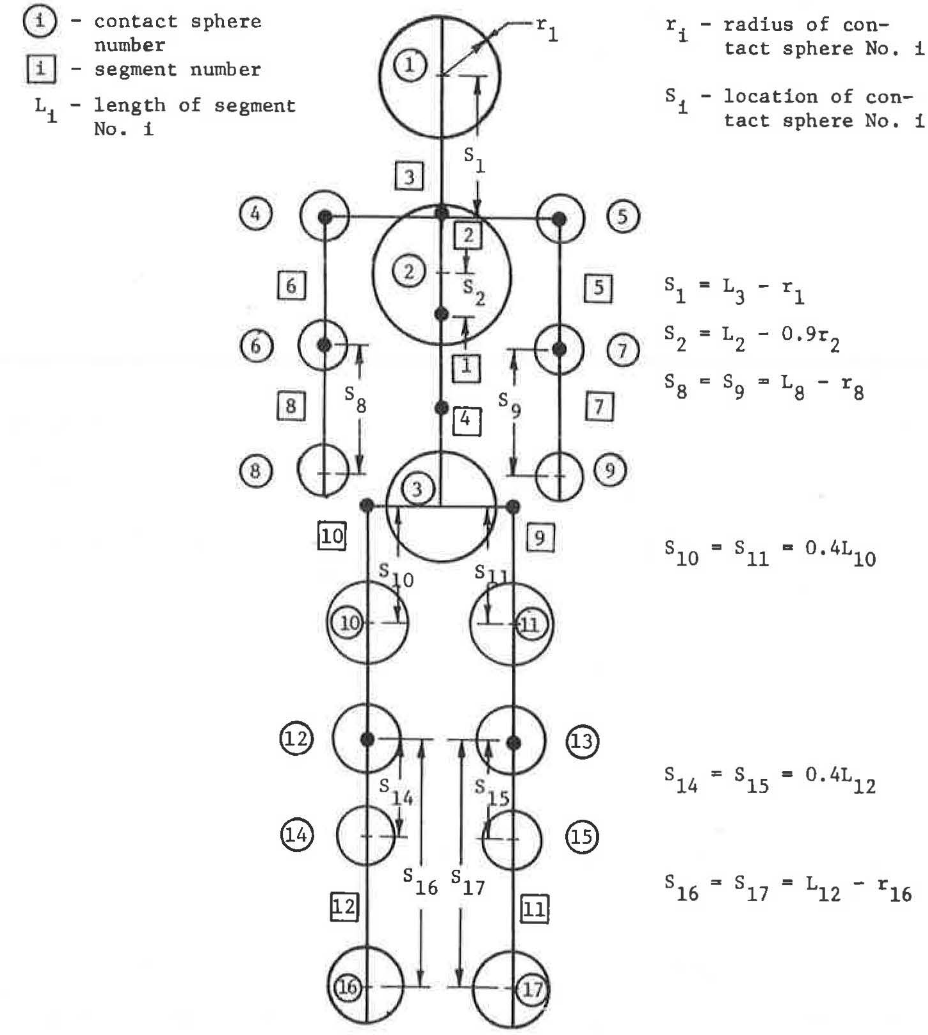

Figure 3. Locations of contact spheres.

The solution of the equations of motion consists of a time history of the following quantities output by the computer program:

1. The coordinates of the end points of each body segment with respect to the vehicle-fixed coordinate system;
2. Acceleration components of the center of mass of each body segment with respect to the segment-fixed coordinate system for that segment (this is total acceleration);
3. Angular acceleration components of each body segment with respect to its segment-fixed coordinate system;
4. Angular velocity components of each body segment with respect to its segment-fixed coordinate system;
5. The force on each body contact sphere plus the identification of whatever vehicle interior surface is being hit;
6. The coordinates of the point of application of the contact force with respect to the center of the contact sphere in segment-fixed coordinates (only for the head, chest, and pelvic area); and
7. The force of restraint applied to the body by the lap and torso restraint belts.

VALIDATION STUDY

An original objective of this project was to validate the passenger model's three-dimensional response capabilities by comparison with existing test data of this nature. To produce conclusive results, any such data should provide the following information:

1. A time history of the vehicle's path in three-dimensional space, preferably numerical instead of photographic (photographic records could be used for application of the passenger model but only after validation);
2. A corresponding time history of the occupant's dynamic behavior, e.g., accelerations, forces, or a photographic record of motion;
3. A quantitative description of the occupant—dimensions, weight, etc.; and
4. Force-deformation properties of the pertinent vehicle surfaces (could be measured).

Unfortunately, test results possessing all these qualities were not to be located and funds for full-scale testing were not available, thus precluding a validation of the general case at this time.

However, suitable test results were available (9) for a partial validation, i.e., the case of a frontal automobile collision.

Test Data

The test data used for comparison were generated at the Biomechanics Research Center of Wayne State University, Detroit, Michigan, under the direction of Cornell Aeronautical Laboratory (CAL), Inc., Buffalo, New York, for the U.S. Public Health Service, March 1967. All experimental results shown in this report were directly from CAL's documentation of these tests (9).

The tests consisted of a dummy seated on a cart capable of controlled deceleration. Mounted on the cart were target assemblies for head, chest, and knee impact. Accelerations of various parts of the dummy and impact forces were measured by instrumentation while the motion of the dummy was recorded on high-speed film. Several cases were run consisting of lap restraint, lap and torso restraint, and no restraint for initial velocities of 10 and 20 mph.

Also measured and documented (9) were the force-deformation characteristics of the targets, seat, and restraint belts plus the dummy's initial position and the amount of friction in each of its joints.

Discussion of Results

Response Comparison for No Restraint at 20-mph Cart Velocity—Figures 4 through 6 show the comparison of dummy kinematics, head forces, and head accelerations for the case of no restraint with 20-mph cart velocity. Agreement between simulated motion and the high-speed film record is excellent. Quantitative comparisons (forces and accelerations) are better than expected because of the idealized vehicle interior (simulation) being geometrically different from the target assemblies used in the test. The simulation utilized a full instrument panel and steering wheel as opposed to isolated targets of about 6 to 8 in. in diameter for the test. This resulted in hand contact in the simulation that was absent during the test. Also, the knee targets were inclined for the test, producing a downward force component, whereas the knees in the simulation contacted a vertical surface (instrument panel) with friction as the only downward force.

Response Comparison for Lap and Torso Restraint at 20-mph Cart Velocity—Figures 7 through 9 show the comparison of dummy kinematics plus head and chest accelerations for the case of lap and torso restraint with 20-mph cart velocity. Agreement between simulated motion and the high-speed film record is good including unsymmetrical body movements as a result of the unsymmetrical torso restraint belt. However, the spring action of the torso belt seems to be excessive in the simulation since the arms are whipped back into the seat as shown in the 0.080-sec frame of Figure 7. This test was subject to the same sources of possible discrepancy as the unrestrained case

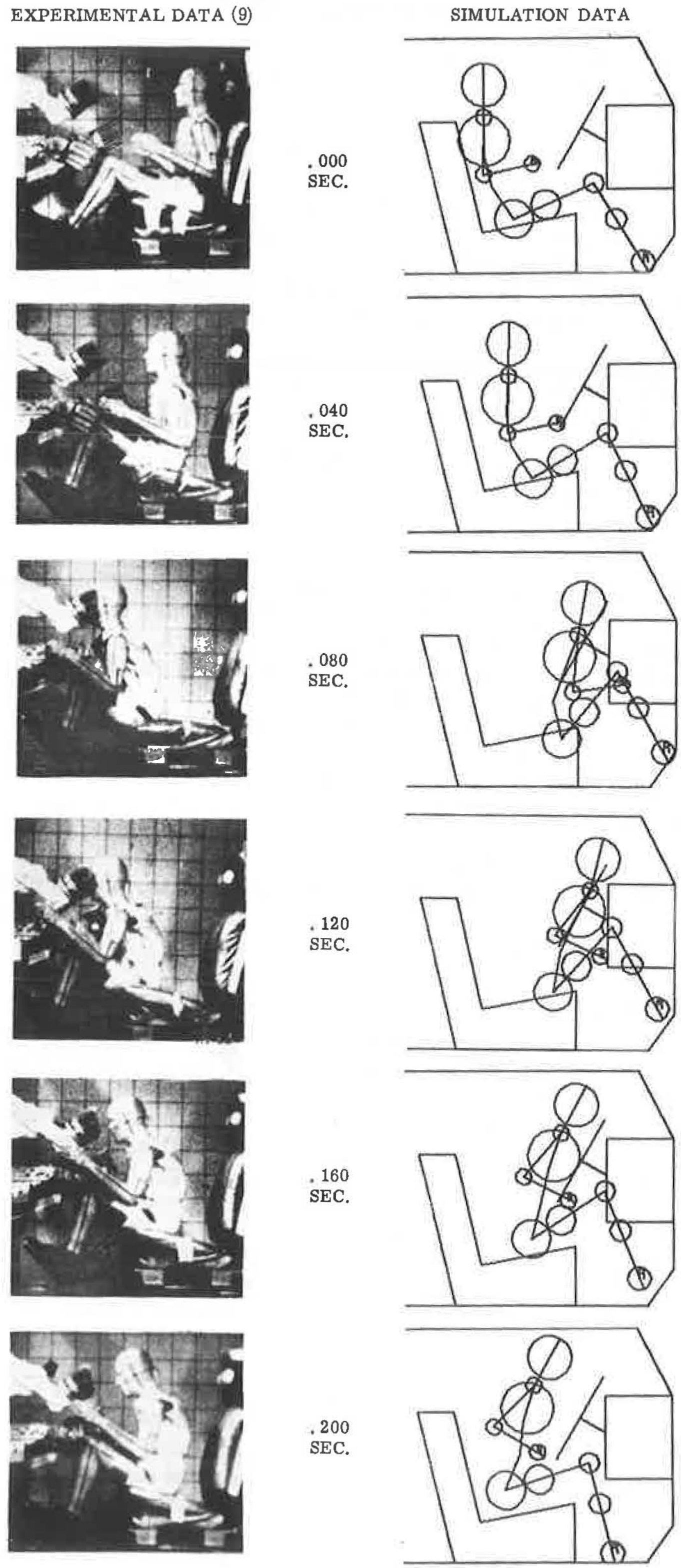

Figure 4. Dummy kinematic comparison, no restraint, 20-mph cart velocity.

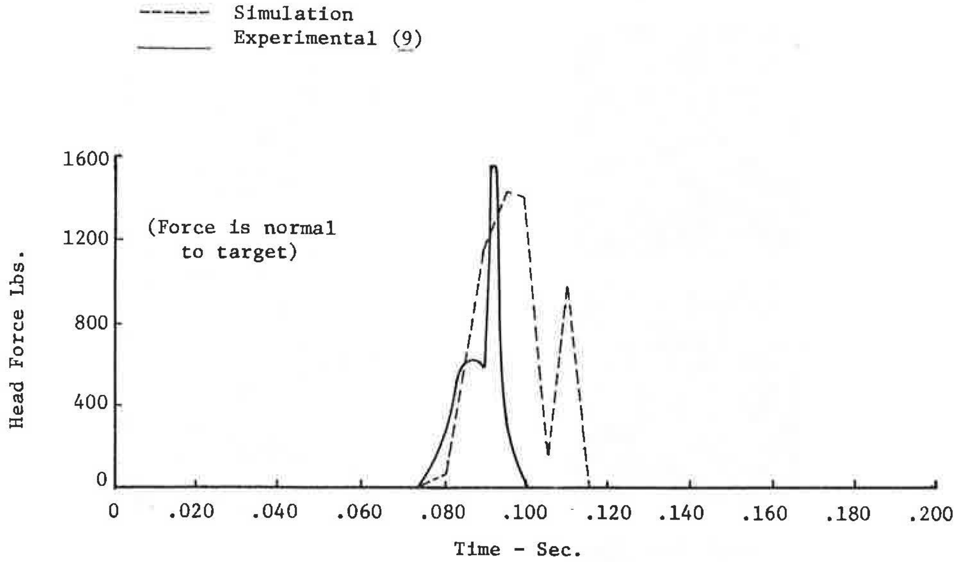

Figure 5. Head force, no restraint, 20-mph cart velocity.

plus an additional one. The anchor points for the ends of the belt were unknown and therefore were estimated for the simulation. This could account for some of the difference in arm kinematics.

Closure—The deceleration pattern used in the test (9) approached a 20-g square wave for a duration of about 0.08 sec. It is interesting to note that the passenger experienced levels of acceleration on the order of 80 g with durations of approximately 0.03 sec for the case of no restraint and levels of approximately 40 g with durations

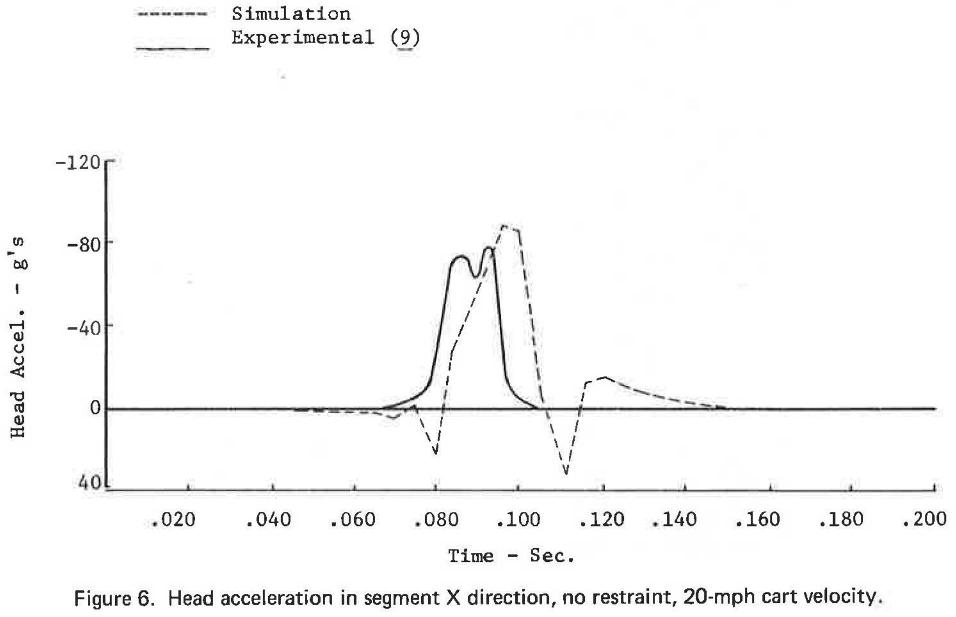

Figure 6. Head acceleration in segment X direction, no restraint, 20-mph cart velocity.

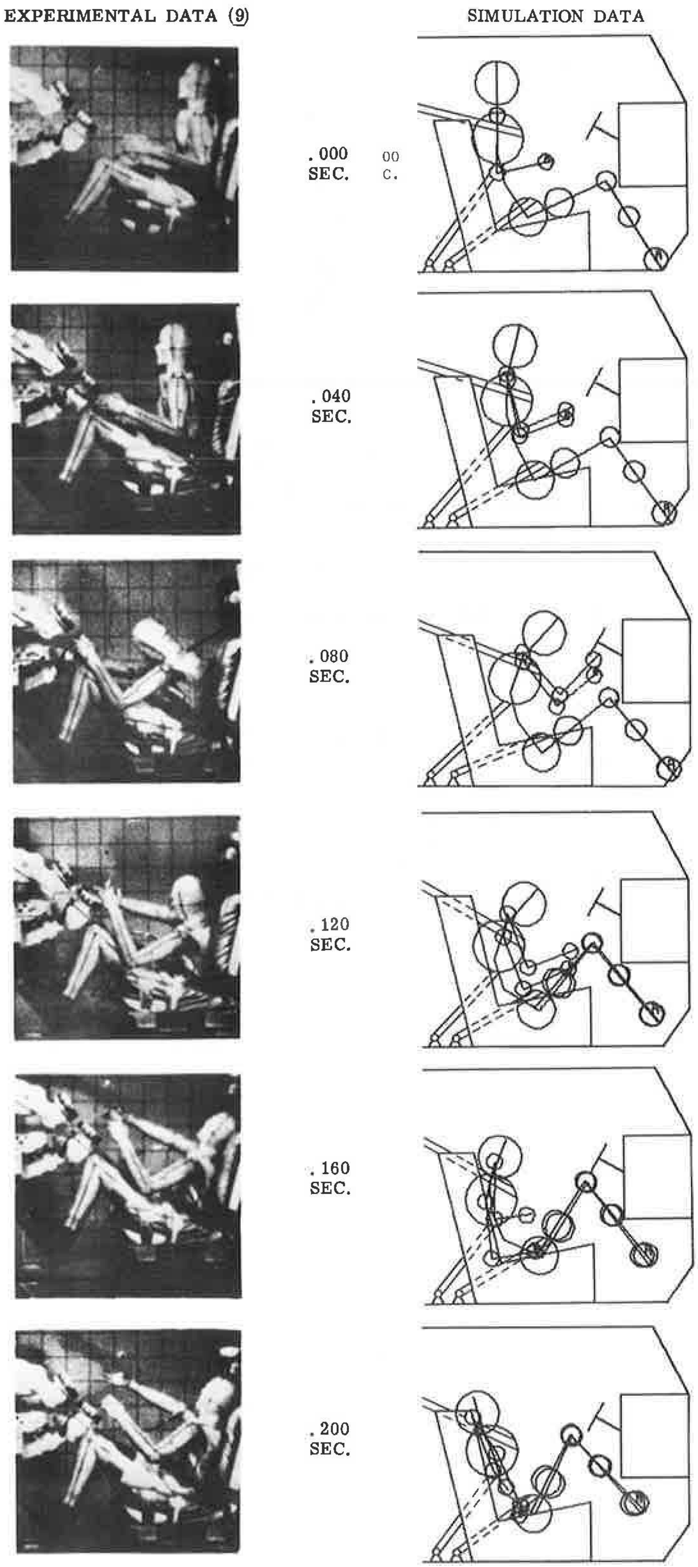

Figure 7. Dummy kinematic comparison, lap and torso restraint, 20-mph cart velocity.

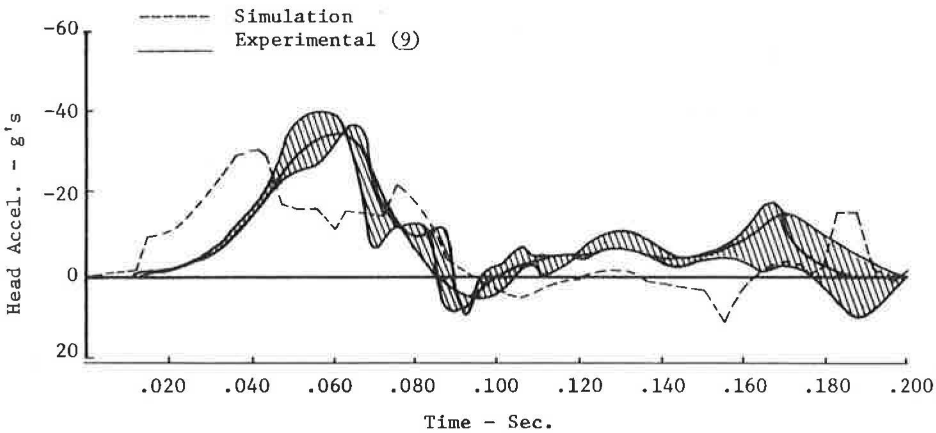

Figure 8. Head acceleration in segment Z direction, lap and torso restraint, 20-mph cart velocity.

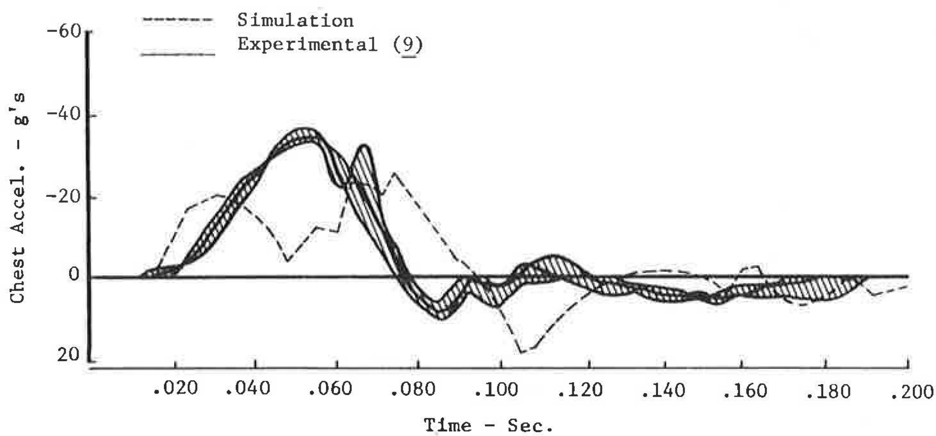

Figure 9. Chest acceleration in segment X direction, lap and torso restraint, 20-mph cart velocity.

of about 0.03 sec for the case of lap and torso restraint. This points to the fact that in some instances the response of the vehicle is no indication of what the passenger actually feels.

CONCLUSIONS

The analytical model described here provides the engineering profession with a useful tool with which to study vehicle and roadway problems, which results in saving lives and reducing occupant injuries. Admittedly, the model was validated for the planar case only; but this in no way precludes its application to three-dimensional motion, especially if qualitative results are being sought.

More specifically, the passenger model reduces the problem of predicting the motion, acceleration, and forces experienced by a vehicle occupant during a collision or violent maneuver of the vehicle to that of specifying the path of the vehicle as a function of time plus the deformation properties of the vehicle interior. (These should reflect the low stiffness property of the human body or dummy, whatever the case may be.) When used with available biomechanics data on human tolerance, the application of the passenger model includes the following:

1. The evaluation of roadway geometry—sideslopes, ditches, terrain involving a variation of vertical and horizontal alignment, etc.; roadside safety features such as the breakaway sign and energy-absorbing impact cushions; and roadside protective barriers such as guardrails, bridge rails, and median barriers;
2. The design of the vehicle interior and restraint systems;
3. The study of the dynamic behavior of a pedestrian when struck by an automobile; and
4. The study of collisions involving more than one vehicle.

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The opinions, findings, and conclusions expressed in this paper are those of the author and not necessarily those of the Federal Highway Administration.

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