ADVANCES TOWARD THE AUTOMATIC HIGHWAY

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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
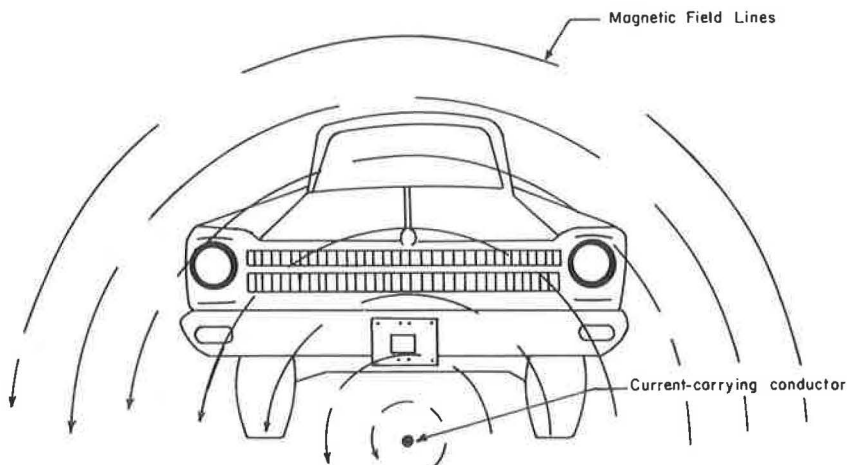

Figure 1. Magnetic guidance field established by one-wire reference system.

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 $7\frac{1}{2}$ 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 $1\frac{1}{2}$-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 $7\frac{1}{2}$ 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
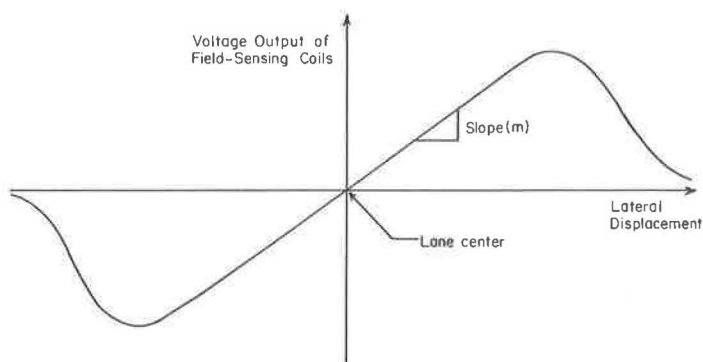

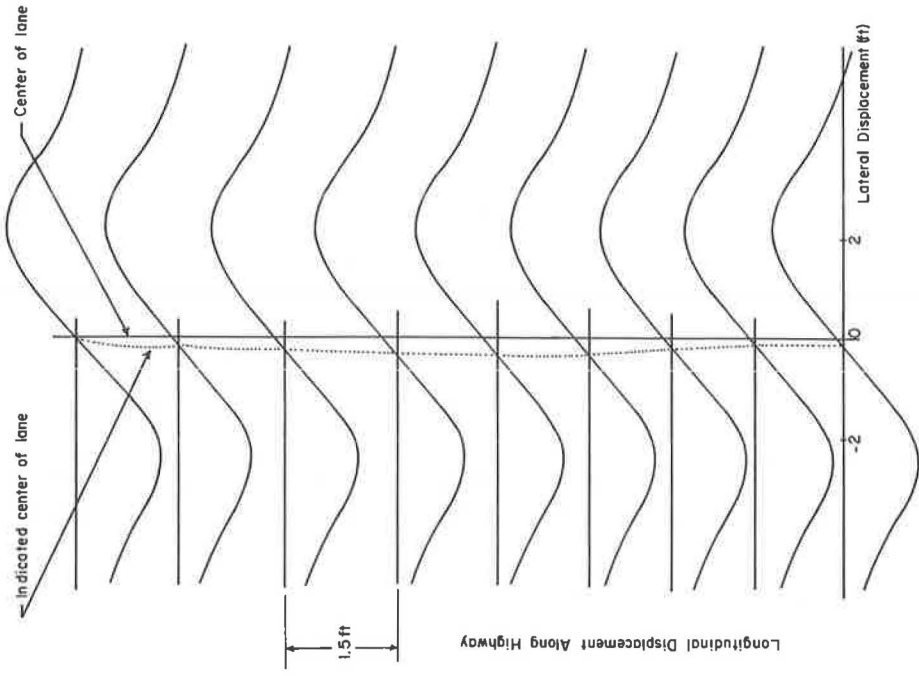Figure 2. Typical error characteristic.

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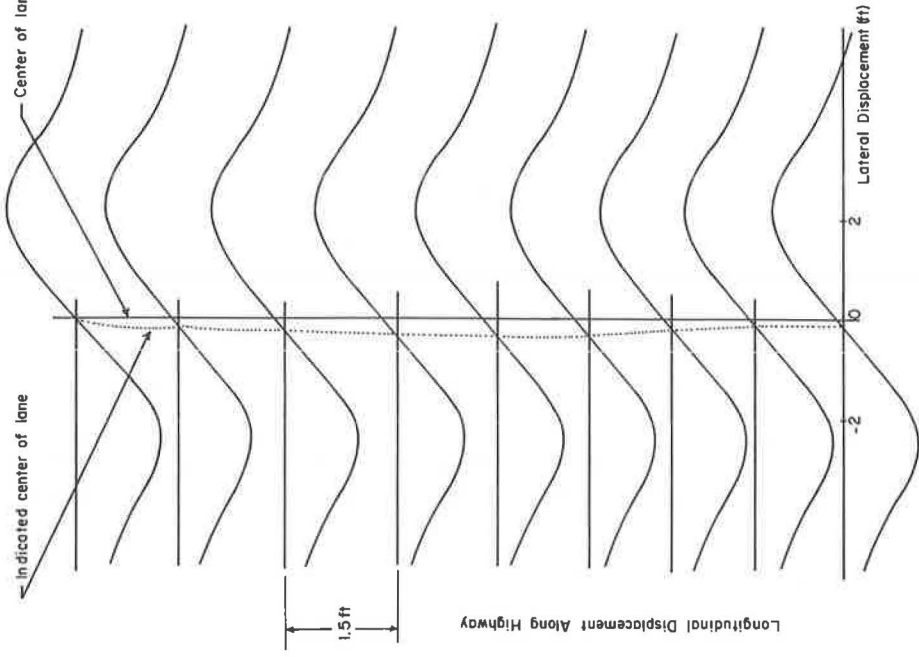Figure 4. Lateral error characteristics for the one-wire system.

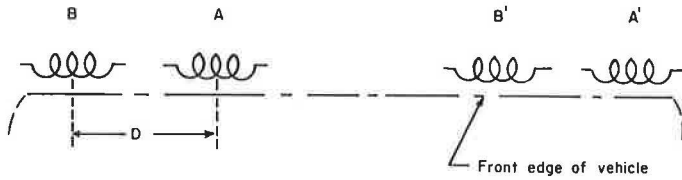Figure 3. Lateral error characteristics for the two-wire system.
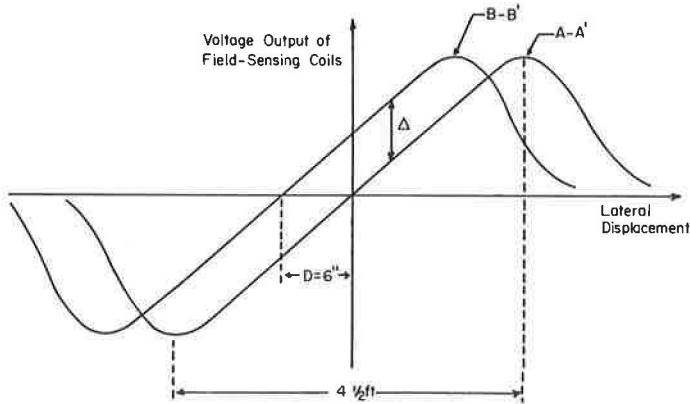
Figure 5. One-wire system coil configuration.

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.
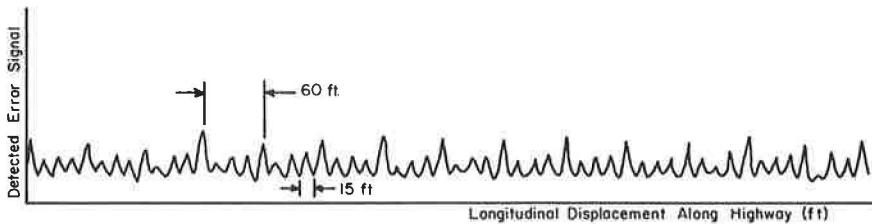

Figure 7. The variational or ac component of Δ.

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
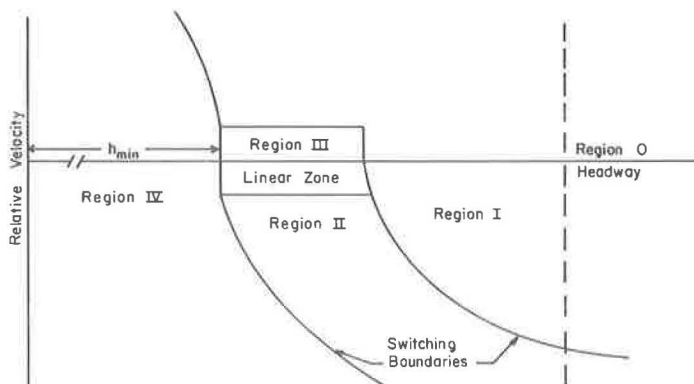

Figure 8. Regions of the phase plane.

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.,

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

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
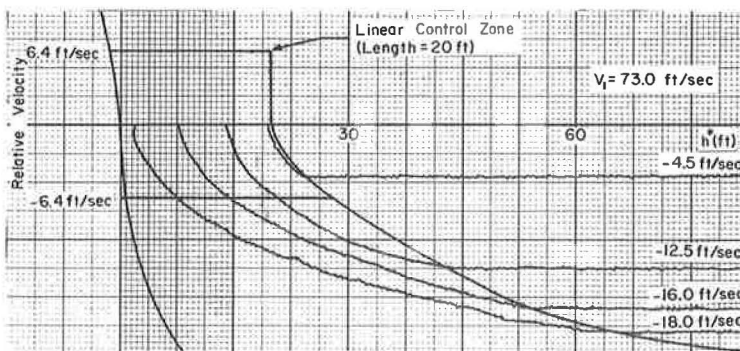

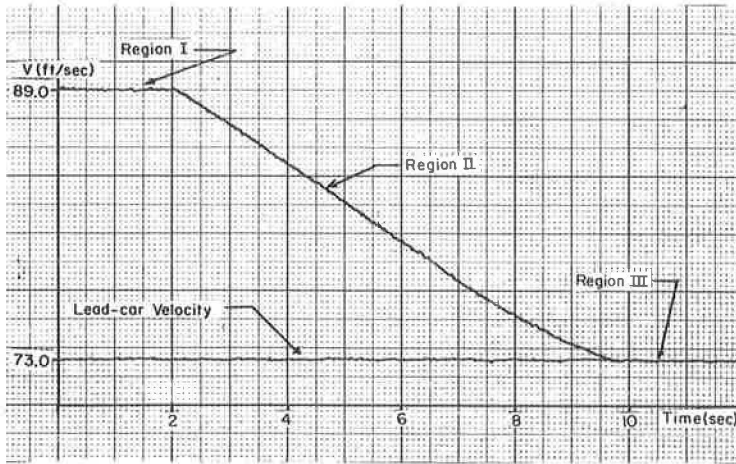Figure 9. Various on-road overtaking situations.

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
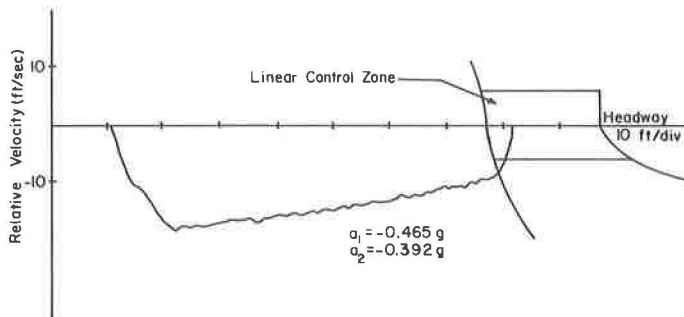

Figure 11. Maximum braking situation (a_2 = 0.392 g).

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
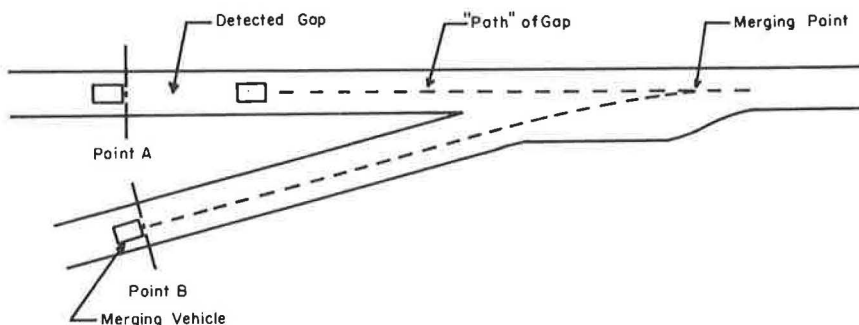

Figure 12. The state of a mainstream-entry ramp configuration when a gap is detected.
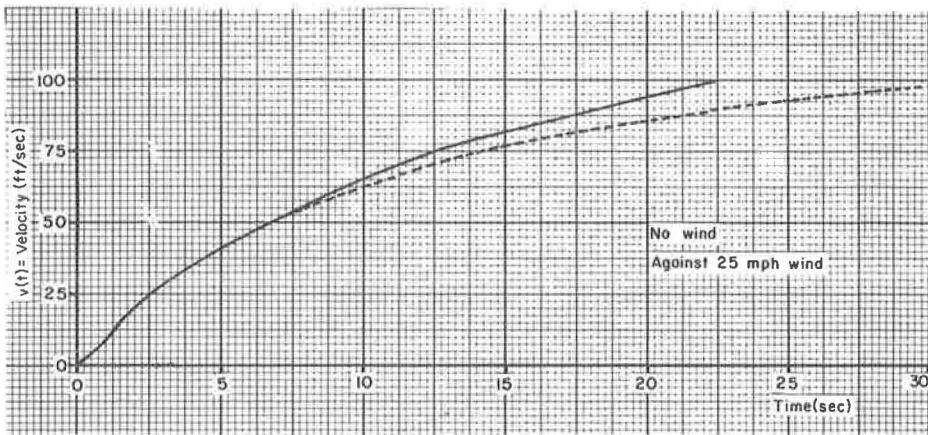
Figure 13. Velocity and distance responses of the test vehicle for a step input of 14 volts (wide-open throttle).

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.
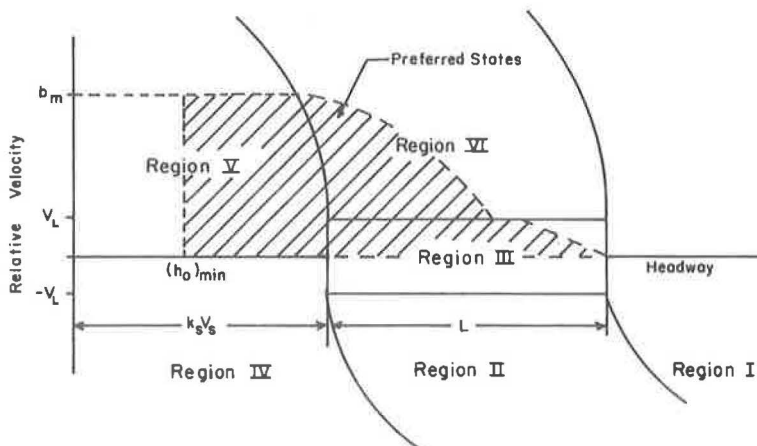

Figure 14. Preferred states of merge insertion.

MANUAL MODE STUDIES

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.

Figure 15. Side-mounted control stick.

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).
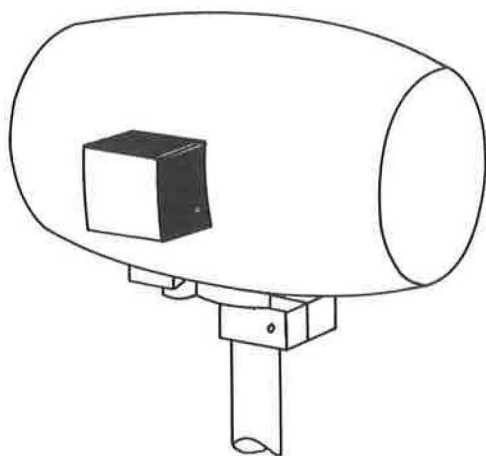

Figure 16. Kinesthetic-tactile display built into head of control stick.

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.
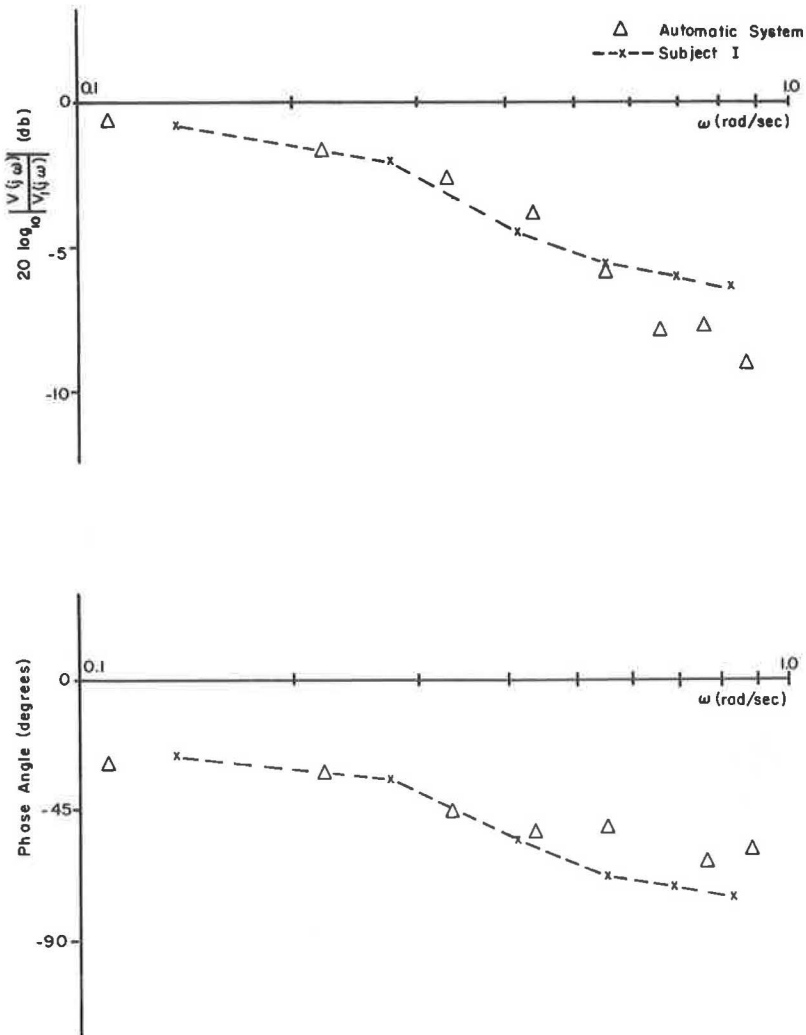

Figure 17. Describing-function models of automatic velocity controller and driver-aided system.

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

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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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