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Mushrooming Technology
new directions in highway safety

Mushrooming Technology:

new directions in highway safety

Robert A. Wolf — *Cornell Aeronautical Laboratory,*

Discussant: John W. Horn

Thomas H. Rockwell — *Ohio State University*

Discussant: Stephen R. Schroeder

John Versace — *Automobile Safety Research Cent*
Ford Motor Company

Discussant: Stanley M. Soliday

NORTH CAROLINA SYMPOSIUM ON HIGHWAY SAFETY

Raleigh, N. C.

Volume four **Spring**

The University of North Carolina Highway Safety Research Center
Chapel Hill, North Carolina 27514 • B. J. Campbell, Director

a few words about the symposium topics . . .

Vision is a prime factor in the driving task. Although there is little research evidence linking vision to driving performance, investigations of visual activity in driving suggest differences among various classes of drivers. Increasing sophistication in methodology and instrumentation has opened the door for further exploration of the role of vision in driving.

Growing traffic demands of the future cannot be met with a corresponding increase in roadways. Resistance is mounting to using more land to build roads. One solution to this dilemma is to use our present system of roadways more efficiently. This can be done in at least two ways: first, by increasing speeds; and second by decreasing headway, or the distance between vehicles. To accomplish this safely it is necessary to employ some form of automation. The automated highway holds promise for handling an increased traffic volume while at the same time decreasing travel time.

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About the Center . . .

At the request of the Governor of North Carolina, the 1965 North Carolina State Legislature provided for the establishment of the University of North Carolina Highway Safety Research Center. Dr. B. J. Campbell, then Head of the Accident Research Branch of Cornell Aeronautical Laboratory, was invited to return to his alma mater to direct the new Center. He accepted, and in 1966 the Center officially began operation. Since then the staff has grown to more than fifty, representing skills in experimental psychology, clinical psychology, mathematics, transportation engineering, computer systems, journalism, library science, biostatistics, graphic arts, epidemiology, experimental statistics, general engineering, human factors engineering, and health administration. The University of North Carolina Highway Safety Research Center is the first institution in the South devoted exclusively to research in highway safety.

About the Symposium . . .

The North Carolina Symposium on Highway Safety is a semiannual event sponsored by the North Carolina State University School of Engineering, the University of North Carolina School of Public Health, and the University of North Carolina Highway Safety Research Center. First held in the fall of 1969, the symposium has three major purposes. First, it is designed to attract students to acquaint them with the problems and possibilities for research in the field of highway safety.

Second, it is a means of bringing together professional workers in the greater North Carolina area whose interests are related to this field.

And, third, the published papers from the symposium will provide on a regular basis major positions and summaries of research in the field of highway safety. It is hoped that these volumes will provide ready resource material for persons interested in this field.

INTRODUCTION

The contribution of technology to highway safety is on the rise. As the driving task becomes more complex and the need grows to move more vehicles at higher rates of speed, we must apply the most sophisticated technology possible, first, to analyze the driving task so that we are better able to teach the necessary skills and design the appropriate vehicles, and, second, to provide, wherever feasible, automated systems of transportation.

Contributors to this symposium present a wide range of technical application. Dr. Rockwell is engaged in eye movement research aimed at analyzing the acquisition of information during the driving task. Dr. Versace has also worked with the role of vision in driving, but his interest lies more in the evaluation of different automotive designs as they relate to human function. Mr. Wolf's paper describes a transportation system that would automate much of the driver's task but which could be developed in conjunction with many of our more familiar transportation systems.

Mr. Wolf presents the case for a dual-mode transportation system. Such a system would combine many of the advantages of the private automobile with the advantages of automatically controlled, high-speed, high-density transportation. The vehicles used could operate under their own power on regular streets but could also lock into a guideway system where speed and headways are automatically controlled. In-city guideways could operate at slower speeds than intercity guideways.

Such a dual-mode system would provide convenience, since the service would be on demand. It would also increase travel speeds and reduce land use for roadways, since the same amount of space would handle many times the number of vehicles that currently can be moved on even our finest expressways. The ecologically concerned might welcome the dual-mode system, since present thinking and planning centers around battery-powered, fume-free vehicles. Like our present automobiles, these vehicles could maneuver in virtually all weather conditions. Because the demands made on the operator would be significantly reduced, many groups that are currently restricted in their mobility could broaden their horizons.

Mr. Wolf traces the history of the dual-mode concept and emphasizes that in formulating plans for future transportation systems much can be learned from existing systems. For example, information concerning the crashworthiness of automobiles is directly applicable to the question of the safety of vehicles used in a dual-mode system. Likewise, our experience with major expressways, railroads, and rail-rapid transit operations, where there is a high degree of control of access and of traffic, should provide clues to many of the problems that are likely to be encountered in a dual-mode system.

The volume of traffic that a dual-mode system can handle depends in large part on the headway that is allowed. There are several ways to determine headway, with safety being traded off for efficiency and vice versa. Here Mr. Wolf pleads for a national policy of tolerance while the questions of headway and volume are explored.

Mr. Wolf emphasizes that it is not necessary to postpone our efforts to develop a dual-mode transportation system. Already there are many places where such a system could be started. He argues strongly, however, that there should be some overall coordination of effort to insure that systems set up in different locations can be linked. Thus, if two cities 500 miles apart develop intracity systems, they should be such that in the future an intercity system could be established to connect the two, and vehicles that function in one city system could function equally well in the other. Mr. Wolf feels that the federal government is the only agency that could provide this coordinating effort effectively.

In the planning and development of any such system that represents a major departure from present modes of transportation, Mr. Wolf points out that it is essential that the sociological aspects of the problem be identified and dealt with. We must determine, for example, the public's level of tolerance for minor collisions on the guideways. When the vehicles are used off the guideway system and under their own power, the level of performance will be lower than that found in standard automobiles. The crashworthiness may also not be up to the standards of present day cars. Because these vehicles will be battery operated, they will not be able to travel long distances without recharging. Public attitude toward such features will be crucial in the successful establishment of a dual-mode system. Consequently, it is essential that the necessary sociological research proceed hand in hand with the technical.

In discussing Mr. Wolf's paper, Mr. Horn points out the importance of examining our transportation system at a time when it is still possible to take steps to provide high speed public transportation on heavily trafficked corridors. If there is much delay in making such an analysis, it may no longer be possible to acquire the necessary land to develop high capacity transportation systems. After describing the advantages and, indeed, the urgent need for high-speed fixed-line systems, Mr. Horn delineates the many advantages of the privately owned automobile and expresses a strong belief that it is here to stay. Consequently, any realistic solution to our traffic problems will of necessity be dual-mode in nature.

The acquisition of information during the driving task is primarily visual. Hence, it is important to analyze this process in order to understand the driving task. Dr. Rockwell is engaged in a large program of research concerned with analyzing the role of vision in driving. He describes the elaborate techniques used in his work and, in doing so, points out the difficulties associated with analyzing the data. Not only is the analysis expensive and time consuming, it also leaves something to be desired in terms of interpretation. First of all, the techniques focus on a restricted field of view. Second, the techniques deal primarily with foveal vision, although driving performance appears to depend heavily on pheripheral vision as well. Third, the fact that a driver is recorded as focusing on an object in no way guarantees that he processed the information thus acquired. Still, eye movement research can contribute much to the understanding of the driving task. Unlike many other measures of driving performance, eye movements do not readily lend themselves to the simulation of "good" performance; that is, the subject is not aware of how he "should" perform.

The eye movement techniques developed in Dr. Rockwell's laboratory have been used to study how driver performance varies as a function of both intra-subject and environmental variables, such as experience, fatigue, alcohol, illumination, and traffic load. His research techniques can also be used to evaluate the effectiveness of different kinds of highway signing to determine which kinds of signs can be read most easily. Different kinds of highway design can be similarly studied.

Perhaps even more exciting are the studies showing important differences between experienced and novice drivers. Compared to novices, skilled drivers concentrate more on the focus of expansion, making greater use of peripheral vision to determine lane position. Novice drivers tend not to adjust their visual sampling as a function of speed as skilled drivers do. The behavior of the experienced driver could be used as a standard against which other drivers could be measured. Not only could such a procedure be used in driver licensing, it could also be used to establish training techniques in driver education. The beginning driver could be taught the kinds of eye movements characteristic of more skilled performance.

As Dr. Rockwell points out, the possibilities for research and application in this area of eye movement have scarcely been scratched.

In responding to Dr. Rockwell's paper, Dr. Schroeder provides a scholarly review of some of the research on oculomotor systems which relate to the functions of eye movement in driving. He discusses systems characteristics of oculomotor control. Here the relevant research views the driver as the critical component in a negative feedback man-machine system. While this approach provides much valuable information, Dr. Schroeder feels that the complexity of the driving task probably imposes limitations on how much it can contribute. More to his liking is research that examines the functional characteristics of oculomotor movement. Here he reports laboratory research (including some of Dr. Rockwell's) that is concerned with the relation between eye movement parameters and the way spatial and temporal information is processed. He recommends dividing the driving task into components that can be analyzed more carefully. Much of such effort, he feels, must take place in a laboratory setting, although laboratory findings must eventually be subjected to field testing.

Dr. Versace reviews the kinds of research that automotive human engineers are pursuing. He points out that they cannot really concern themselves with accident avoidance, since there are so many uncontrolled and indefinite variables involved. For example, if there is a failure in the brake system, a driver may resort to hand brakes and thus avoid a crash. If weather conditions create hazardous roadways, the driver may decrease his speed. Because driver adaptation can compensate for such a wide range of problems, it is more efficient for the human engineer to concentrate on the problem of injury once a crash has occurred. The effectiveness of changes in design can be readily measured against a criterion of injury reduction, while it is much more difficult to measure against a criterion of accident prevention.

Dr. Versace describes three specific areas of human factors research, namely, vision, anthropometrics, and biomechanics. For the automotive human engineer vision research is, to a large extent, concerned with lighting systems. Much of the work takes place in the laboratory, but there remain problems in generalizing from the laboratory to the real world. For example, to detect differences among various signal or lighting systems, researchers load the subjects with other tasks so that it is more difficult for them to concentrate on the visual discrimination under scrutiny. Yet there is no way to determine how the degree of loading in the laboratory compares with the degree of loading in a genuine traffic situation.

Anthropometry also is concerned with vision, for in vehicle design one must determine where the driver's eyes are located to make sure that his line of vision is not obstructed. Anthropometry also deals with the interior dimensions, so that controls are placed within the reach of the operator. There is a large variety of possible arrangements of interior vehicle features. Such parameters as steering wheel size and angle relative to the accelerator, or the relation between the seat location and foot pedals, can be combined into numerous test packages which are then evaluated. Because actual testing of all possible packages is not economically feasible, mathematical procedures are used to analyze the different packages.

Biomechanics concerns the occupants' susceptibility to injury. Obvious obstacles to research exist in this area when it comes to the question of subjects, so that it is essential to develop laboratory procedures that will approximate the results that would be found in actual crashes. Dr. Versace takes the position that one can get too involved with the difficulties posed by this kind of research. He prefers to concentrate on the vehicle characteristics.

Dr. Soliday comments on Dr. Versace's discussion of the driver's role in accident avoidance. While there is much validity to the notion that the driver can and does take evasive action in potential accident-producing situations, there are other times when the driver is helpless to affect the outcome. Dr. Soliday feels that it should be possible to develop warning systems to inform the driver of impending danger while there is still time for intervention. Dr. Soliday also endorses Dr. Versace's concern about the validity of extrapolations that are made from laboratory findings to the real driving task.

Dr. Rockwell's work focuses on the role of vision in the driving task. Dr. Versace is concerned with vision, as well as other variables, in his analyses of the vehicle-occupant configuration. Mr. Wolf is looking to the day when the driver's role will be minimized, with an accompanying increase in the safety of the entire system.

Patricia F. Waller

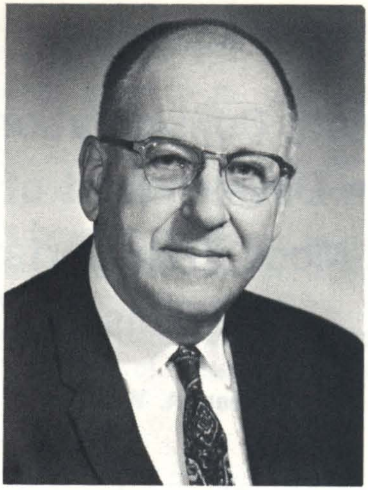
Section I

Safety Considerations in Development of Dual-Mode Transportation Systems

Robert A. Wolf

Discussant

J. W. Horn



ROBERT A. WOLF

Mr. Wolf continues a long and illustrious career in transportation research. From 1932 to 1951 he was poineering in the development of advanced types of military aircraft. The first Air Force turbo-jet and several early Bell Aircraft Corporation helicopters were developed under his direction.

Since 1951 he has been with Cornell Aeronautical Laboratory, Inc. From 1957 to 1961 he headed their Operations Research Department, where his work concerned military tactics and strategy, as well as technical characteristics of physical equipment such as aircraft, weapons, radars, and command and control systems. From 1961 to 1969 he directed CAL's Transportation Research Department, which was devoted to applied research in the technical and operational aspects of highway, urban transit, and military transportation systems.

Mr. Wolf is now Head of CAL's Transportation Systems Research Group, which is a multi-disciplinary unit concerned primarily with new concepts of urban and intercity mass transportation. The mission of the unit ranges from system and component conceptualization, simulation, design, and experimental development, to full scale demonstration.

Mushrooming Technology: new directions in highway safety

North Carolina Symposium
on Highway Safety

volume four

SAFETY CONSIDERATIONS IN DEVELOPMENT OF DUAL-MODE TRANSPORTATION SYSTEMS

By Robert A. Wolf

For many years, Cornell Aeronautical Laboratory (CAL) has been conducting studies and evaluations of different forms of future transportation systems. These systems have the potential to reduce urban highway congestion and air pollution; constrain over-expansion of urban expressways; and, at the same time, improve door-to-door transportation service for city and suburban dwellers. We have identified a transportation system concept, called the Dual-Mode system, which combines the convenience and flexibility of the automobile with the ability to provide a new form of mass transit. CAL coined the word "Urbmobile" to represent this class of system. (In this paper, the terms Urbmobile and Dual-Mode will be considered as synonymous.)

It is hoped the concept of the dual-mode system will soon gain federal attention and emerge as a leading contender for a new form of urban, intercity, personalized travel, suitable for national application.

In expectation of a growing interest in automatic transportation systems, reference has been made to a large portion of the available literature, and attempts have been made to anticipate some of the safety problems which might be encountered in development of these systems, especially those problems related to dual-mode guideway design, automatic control, and in-station operations.

This paper suggests a systematic approach to identifying possible hazards and possible solutions to problems that occur during the period of conceptualization, when systems are described only in concept, rather than as tangible hardware. The basic tenets in the approach are as follows:

- Define a technically feasible system to meet the gross conceptual functions, and then think it through, step-by-step, in its detailed operational functions and processes, attempting to visualize and describe potentially hazardous events.
- Once grossly conceived, it is possible to identify expected problem areas by examining the accident records of existing systems

that provide similar functions, and present the question to you: Are these types of accidents likely to occur in my new system?

- Apply formal analytical procedures, such as mathematical modeling, simulation, error analysis, failure mode analysis, and reliability analysis, that will help establish research priorities; but these procedures, if used with imagination, will also suggest possible solutions.

In conducting the brief exercise discussed herein, be aware of and consider the following: that a broad coverage of system safety must concern not only the passengers, but also system maintenance and operating personnel, as well as innocent bystanders and intruders; that the importance of property damage and economic losses merits special attention; that human "failures" will arise even in a so-called automatic system; that many of the day-to-day operational rules of safety must and will be established through experience with real systems as they evolve; that it is unrealistic to expect that the system designers and engineers, in their first attempts, will anticipate all modes and degrees of failure (but it is hoped that some preliminary insight to avoid and mitigate accidents may be gained from examining accident events and safety procedures for other types of systems); and, finally, that determination of public acceptance of risk is unrealistic at the conceptual stage of evolution.

INTRODUCTION

For almost a decade, my colleagues and I at the Cornell Aeronautical Laboratory have been grappling with the technical, economic, and sociological problems of the automobile. Much of this effort has been devoted to contemporary highway safety, but I have also been personally fascinated by the idea of the automatic highway, with its technical challenge and its promise of improving safety, increasing speed, and increasing capacity for moving people and goods. The increasing pressures of automobile traffic congestion and air pollution, as well as the general public interest in preserving our ecology, may provide society with the needed incentive to accept these new and advanced forms of automatic transportation that are now technically feasible but not yet exposed to public trial.

My earlier career in design and development of advanced aircraft, and my present exposure to the CAL's broad range of technology, applied to all forms of transportation, be it land, sea or air, has provided a perspective which convinces me that the system I will describe as technically feasible, as well as socially acceptable and economically viable. I suggest that this dual-mode transportation system concept (urbmobile) is one of the most promising and exciting new earth-bound ideas that has come over the horizon in many a moon. There is, however, much inertia to be overcome before it can be converted from an idea to reality.

This futuristic concept, one of the family of possible automatic highway schemes, offers great promise in helping to solve the increasing problems of traffic congestion, parking space, air pollution, noise pollution, and expressway sprawl. Several private firms are experimenting with the idea, but it has not yet been committed for research and development by the U.S. Department of Transportation (DOT). I hope that this concept will soon be "discovered" and promoted by DOT, and in this paper I will mention sound reasons for this position.

The dual-mode is a transportation system concept in which an identical vehicle can be driven on streets or highways, self-powered under manual control; and can also enter a special guideway, pick up additional power, and be propelled under automatic control without an operator or driver. A variety of vehicle types can be accommodated, ranging from small personalized cars, to buses and freight carriers. These vehicles can, of course, also operate exclusively in either of their single modes.

The guided mode is especially attractive as the first developmental phase of an automatic system for smaller cities, new towns, supercampuses and airports. The manually operated vehicle can be introduced later as a collector-distributor bus. In its full blown, dual-mode configuration, the unmatched door-to-door convenience of the automobile and the high-speed and great capacity of rapid transit are combined.

Some of the attractive attributes of the dual-mode system are listed below:

- Convenience — Door-to-Door, personalized service or On-Demand service when in the public transit configuration.
- Speed — Intracity 50-75 mph, Intercity 75-100 mph.
- Capaciousness — High Capacity; one guideway lane equals several expressway lanes.
- Fume Free — Electric Propulsion.
- Flexibility — Mass Transit, Personalized Private Transit, Freight, and Combinations.
- Weatherability — All weather on Guideway—same as auto on roads.
- Stimulating — New mobility opportunities for young, aged, infirm, "underprivileged."
- Universality — Regions, Cities, New Towns, Airports, Super-campuses.

A variety of vehicle guidance and control schemes are possible within the urbmobile context, but each design is intimately bound up with the specific type of vehicle propulsion, guidance concept, and guideway configuration being considered. Therefore, many designers will emerge and it will be necessary for some central, authoritative agency to continuously monitor different dual-mode designs to eventually bring their guideways into an integrated and useful national network. Thus, once the basic dual-mode concept is launched and the "ball gets rolling," there will be a period of a decade or so during which various subsystem designs will emerge and be "wrung out" in experimental form before the desired and necessary standardization of guideway and vehicle control system will allow national application. Eventual convergence on a "standardized" guideway concept is imperative and the federal government should act as umpire and decision maker in this task. In addition, I believe that this overall system concept has such broad social, economic, and institutional implications that the federal government should aggressively lead the research, development, and evaluation of the dual-mode concept as a project of national importance, rather than allowing it to emerge "willy-nilly," according to the whims and prejudices of private development.

My role as an advocate of the dual-mode cause is based on the strong conviction that it will provide greatest public benefit only if it is designed, phased, and integrated properly into the existing highway and rapid transit systems by an agency having powers of decision or persuasion much broader than those of local political constituencies or private industry; and that it should initially be accepted or rejected on the basis of its merit for public service and social improvement rather than solely on a profit motive.

Concerning guideway standardization, there is a vast difference between dual-mode and rail rapid transit (RRT) systems. RRT guideway systems for each city, can have a different design because they are self-contained and autonomous; and the rolling stock of adjacent cities need not be compatible as it always remains on its own "guideway" and does not mix with its neighbor's system.

The dual-mode system by its very definition requires both automatic guideways and normal roadways, and planners should not fall into the trap of thinking in terms of limited local utility, which is so characteristic of RRT. From the very beginning, dual-mode should be considered as a more universal system that allows travel from city to city and state to state. For initial installations, it may be sensible to phase in local dual-mode systems solely for public transit service where operation of the guideway and rolling stock is the responsibility of the system manager. This would be continued until a time when the private, manual mode becomes practically realizable. As cities and their populations overlap, the populace of any one of a pair of adjacent cities should be able to move freely on compatible guideways. The nation should not allow proprietary interests to create "walled cities" or regions. The responsibility to standardize guideway design for the public benefit should rest with decision-makers at the national level.

It is interesting to note that, at the present time, several single-mode, low-speed, automatic transportation systems, capable of "on-demand" service are being developed in the United States. It is hoped that experience gained in developing automatic control for these first generation single-mode designs will contribute ultimately to the evolution of true dual-mode control systems capable of handling higher speeds. These, and other developments, as well as control system studies are mentioned in the references.

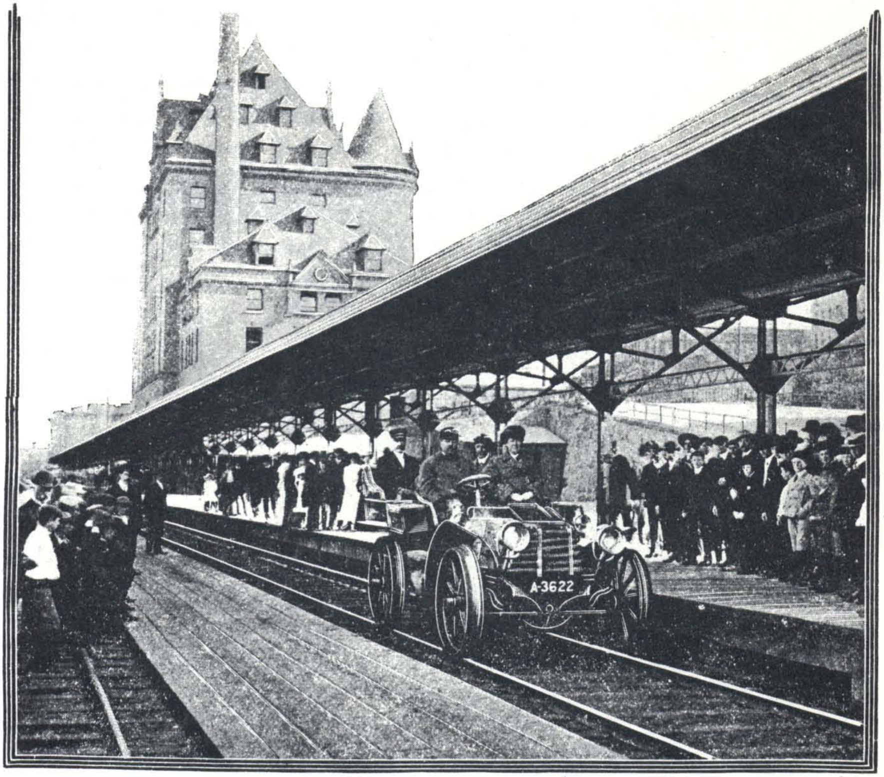
EVOLUTION OF THE CONCEPT

Before we discuss the anticipated safety problems of the dual-mode system, let's consider a few bits of history in the evolution of the dual-mode concept and also get more familiar with its essential elements.

The first record we have found of a highway-type vehicle that could traverse a guideway was a converted 24 hp Napier automobile modified by Mr. Charles Glidden of Boston in 1904. It was not a true dual-mode vehicle but once mounted on rails, Glidden drove it from coast to coast on railroad tracks under its own power. Figure 1 shows Glidden's steel-wheeled automobile as it finished a transcontinental run in Vancouver, B.C., in 1904, with an actual running time of 155 hours. The steel-flanged wheels used were 40 inches in diameter.

A combination electric- and gasoline-powered dual-mode bus was operated in New Jersey during the mid-1930s. Recently there have been some trials with converted buses, called rail buses, running on rail right-of-ways, in an attempt to find use for abandoned or infrequently used railroad tracks. These vehicles used their rubber tires for traction, had retractable flanged steel wheel bogies for guidance, and have been propelled by internal combustion engines.

The very early trials were strongly vehicle-oriented, and their proponents never dreamed of the all-important and complex automatic control systems needed to provide a truly useful dual-mode system. Automatic vehicle guidance was suggested by two sources in the mid-1960s; one in a brief description of the StaRRcar concept by William Alden in 1963 and another in a description of the Commucar idea devised by a group of MIT students in a 1964 study project. These sources, however, at that time, did not define the all-important, overall command and control system. The Alden Self-Transit Corporation continued to develop the idea and, at present, is concentrating on a single-mode experimental vehicle and automatic control system. Dual-mode versions will come later when the time is right.



"MOTOR AGE" OCTOBER 6, 1904

FIGURE 1. *Arrival of Mr. and Mrs. Glidden at Vancouver.*

CAL's role in defining a concept for a dual-mode, electrically powered vehicle transportation system began more than six years ago. Our original study for the federal government, in which we identifed the concept as a leading candidate for national development, was conducted in 1964 for the Department of Commerce. (Cornell Aeronautical Laboratories, Inc., 1964) We coined the term "urbmobile" to describe this emerging class of new systems because we felt the need for an identifiable generic descriptor. Further study of the technical and economical feasibility of the dual-mode transportation concept was conducted by CAL for the U.S. Department of Housing and Urban Development (HUD) in 1967 (Cornell Aeronautical Laboratory, Inc., March 1968). In this pioneering study, CAL identified and described feasible engineering solutions to the heretofore conceptual functions of the generic dual-mode system. We also described a complete, illustrative urban system including guideway network, vehicles, stations, automatic vehicle guidance, traffic control, automatic parking, and guideway structure for a typical city of about one-half million population.

The particular system defined in CAL's study for HUD used a rail-guided vehicle, labeled Urbmobile MK-I, because we considered it the first approximation in a series of evolving designs. A distinguishing feature of the MK-I concept is the use of a synchronous motor, driving steel flanged wheels for guidance, traction, and braking on the rail-type guideway. Some illustrations of the rail-guided system are used here to point out basic functions and elements of the generic dual-mode system concept. Obviously, there are many other possible combinations of propulsion, guidance, and control but suitable illustrations of them are not readily available.

After the initial jocularity that confronts most innovative ideas wore off, the urbmobile idea began to attract attention. Figure 2 shows some characteristic features of the urbmobile, such as numerous vehicles on the mainline, close headways, rail guidance, third power pickup, and automatic "hands-off" control.

Figure 3 illustrates a stable of vehicles ranging from a small, personal car, to a 15-20 place bus. Also, note several special service types for the aged, the young, the infirm, as well as for mail carrying, package delivery, and light freight, wherein "drivers," when on the

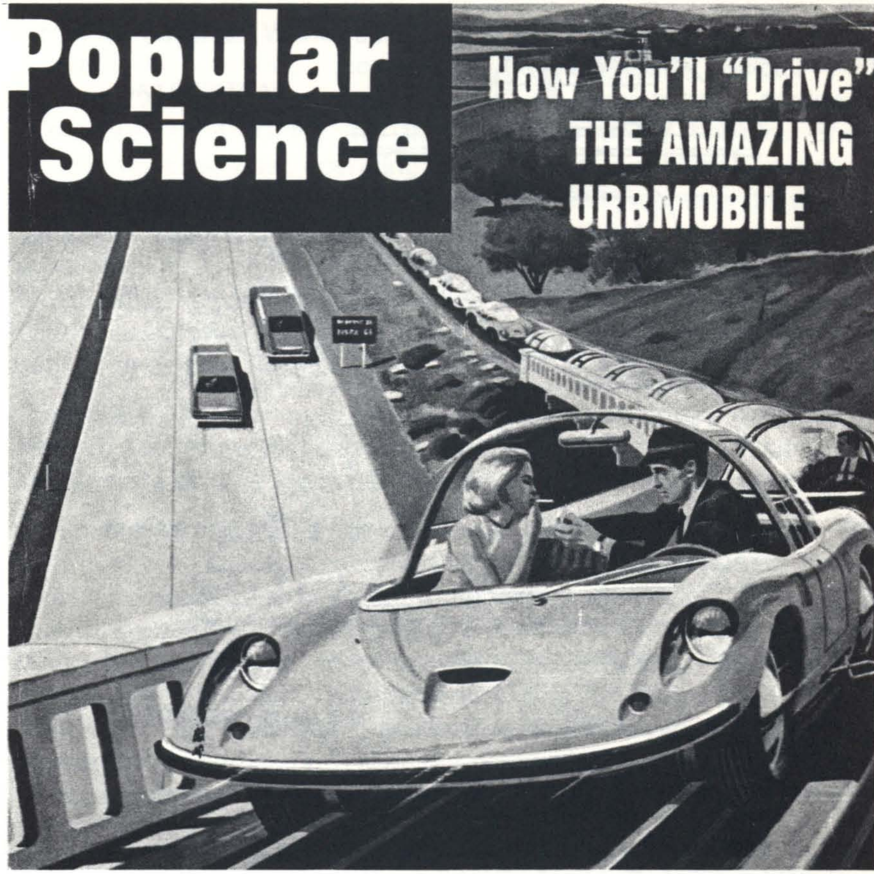


FIGURE 2. *Characteristic features of Urbmobile.*

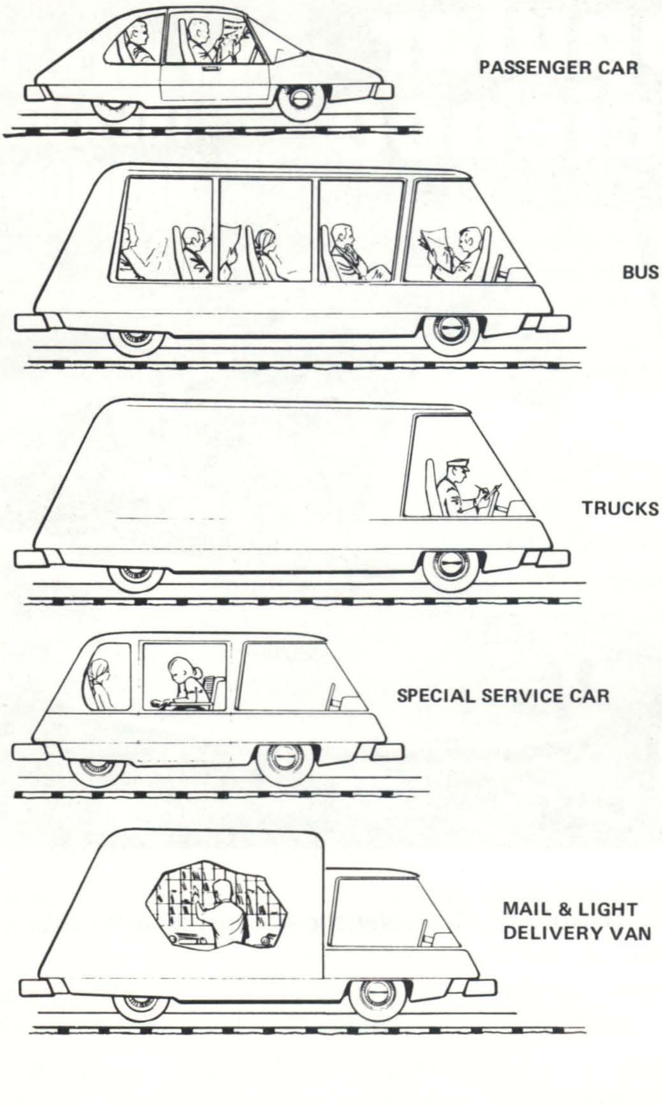


FIGURE 3. *A family of Urbmobile vehicles.*

guideway, are occupied with other duties. One of our recent, continuing studies was concerned with preliminary engineering of this family of vehicles. Within our limits of time and funds we managed to outline the Urbmobus and the Special Service Utility vehicle, which bracket a weight range from about 8000 lbs. gross for a 15-passenger Urbmobus, to 3700 lbs. for the four-place Utility Vehicle. These electric vehicles, when operating on guideways, would pick up central power from a third rail, and on streets, would operate on storage batteries. Lead-acid batteries, deficient as they are in energy and power density for a "competitive" electric automobile, are adequate for an initial trial of dual-mode. Improvements derived from the sizable battery research program now going on throughout the world can be applied in a later phase.

Figure 4 shows a cross section of one version of the combination flanged steel wheel and pneumatic tire, which may be a bit confusing as two sizes of tires are superimposed on the preliminary layout.

A major component of the dual-mode system is the guideway. The MK-I guideway utilizes steel rails and third-rail, three-phase AC power. Propulsion is by means of AC squirrel-cage induction motors. This type of synchronous system allows a desired on-line speed to be set by the system operator. Individual vehicles—or trains—would seek to null on the set velocity (like electric clocks synchronize). Exit of a vehicle from the guideway is achieved through in-vehicle switching by predetermined setting of the desired destination. Conventional switching operations are too slow to allow rapid exit before a close-following vehicle arrives at the switch-point.

Figure 5 shows some of the guideway features. Here a vehicle is exiting to the right. The third-rail power pickup arm disengages as the vehicle rolls through the switch. A finger, on both front and rear axles, has been extended by a solenoid after a signal for the vehicle to depart was received from a trackside computer. The finger is about to engage the curved exit slot and the vehicle will roll on its rubber tires on the surfaces provided and will then re-engage the steel tracks on the exit ramp.

Figure 6 illustrates one possible type of guideway. The two guide lanes are each eight feet wide and between them there is a nine-foot

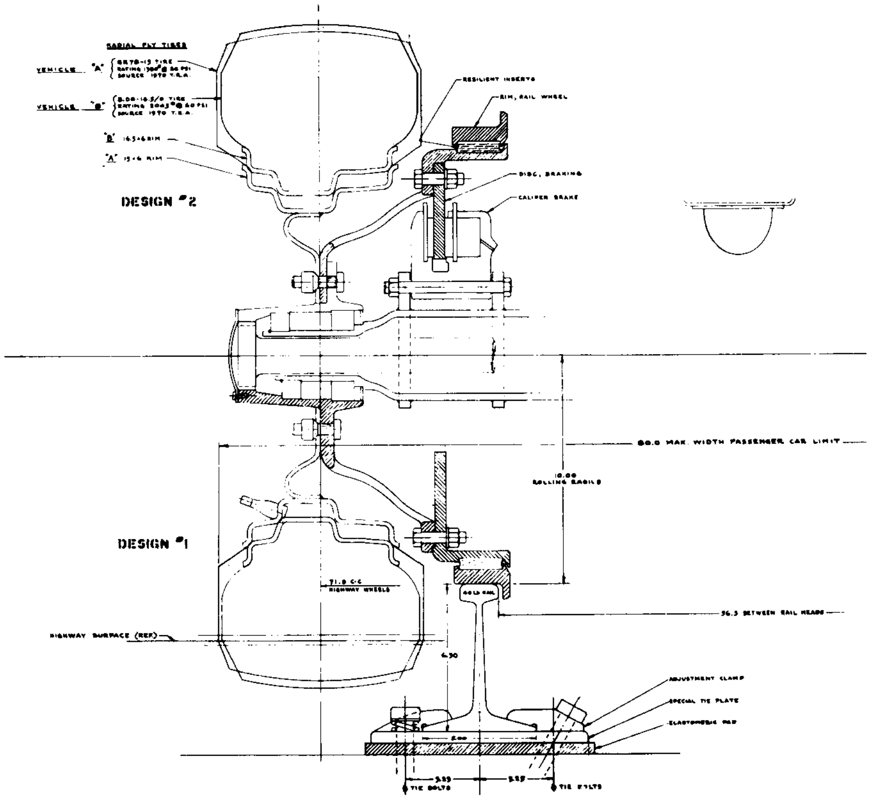


FIGURE 4. *Flanged steel wheel configuration.*

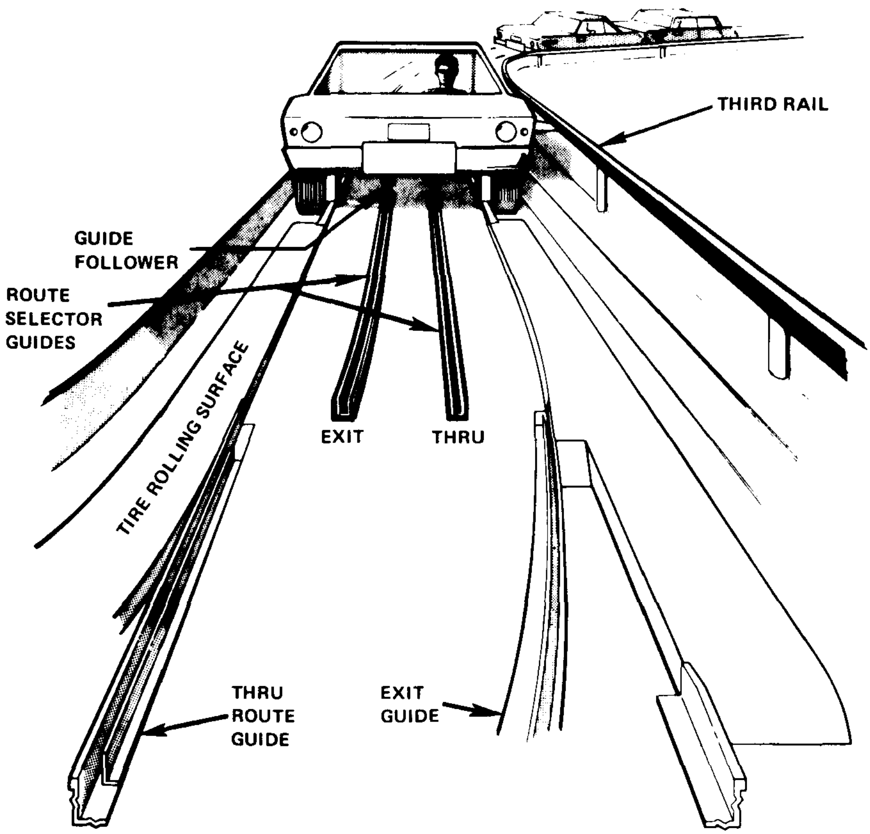


FIGURE 5. *Urbmobile guideway exit.*

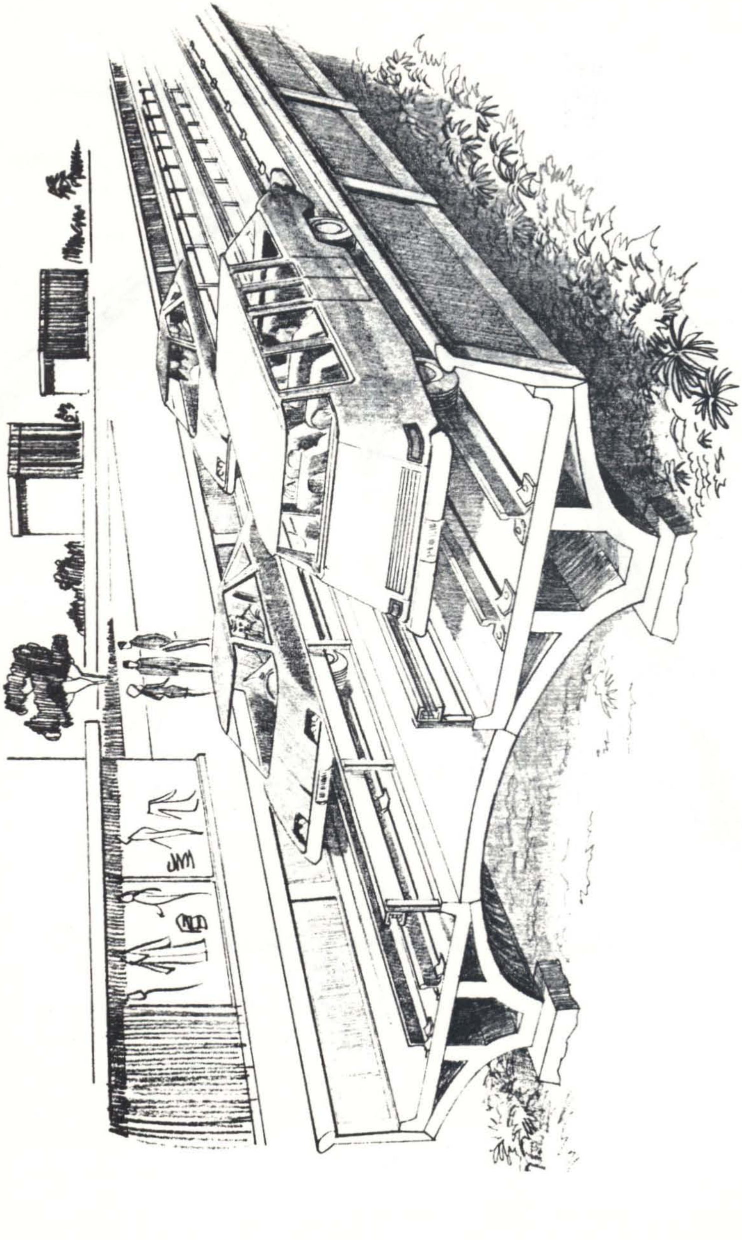


FIGURE 6. *Urbmobile MK-1 guideway.*

emergency and service lane. If an urbmobile develops trouble, the service lane provides access for a special emergency service vehicle to drive to the disabled car and lift it bodily from the tracks. Thus the guideway will suffer only a nominal "down" time. Guideways can operate at grade level, on elevated structures, in open cuts, or underground. They must, of course, be grade-separated when crossing streets and roads.

Figure 7 illustrates how an elevated type of installation could be built on an existing city street.

Figure 8 shows how an open-cut arrangement can be handled in an existing city. At street crossings the guideway would underpass the street level.

Design of entry ramps to provide automatic acceleration, gap opening, and merge is a major technical challenge. At merge points there is a local block control system built into the guideway to sense on-line vehicle position and spacing. A local computer controls on-line vehicles to produce suitable gaps for entering vehicles, whose acceleration and merge is also controlled by the computer.

Figure 9 shows the following sequence:

- A vehicle is standing at the curved acceleration ramp awaiting the start signal. A group of main-line vehicles on an approximate collision course is acquired by the computerized upstream surveillance system.
- Automatic control system begins to open a gap.
- The gap widens.
- When a proper gap is created, the entering vehicle starts acceleration.
- Acceleration on a controlled "profile" is continued.
- Entering vehicle closes on the gap.
- Entering vehicle merges into the gap.

If something had gone wrong during the automatic acceleration process, the entering vehicle would have been diverted into an abort loop before it reached the main line.

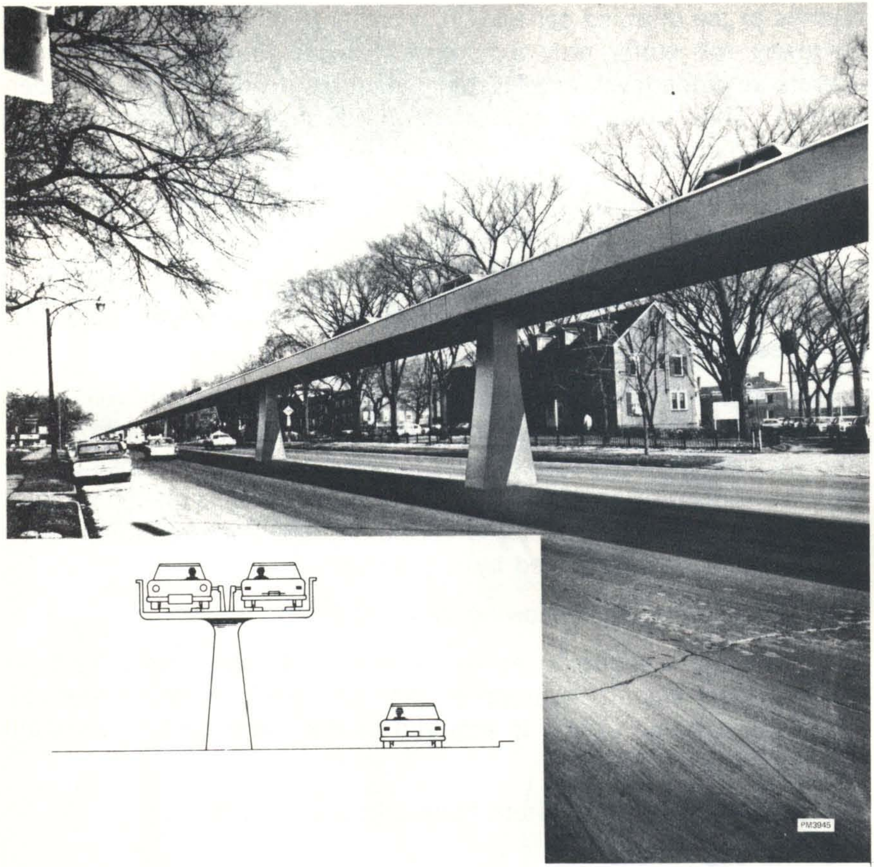


FIGURE 7. *Elevated guideway in center of an arterial.*

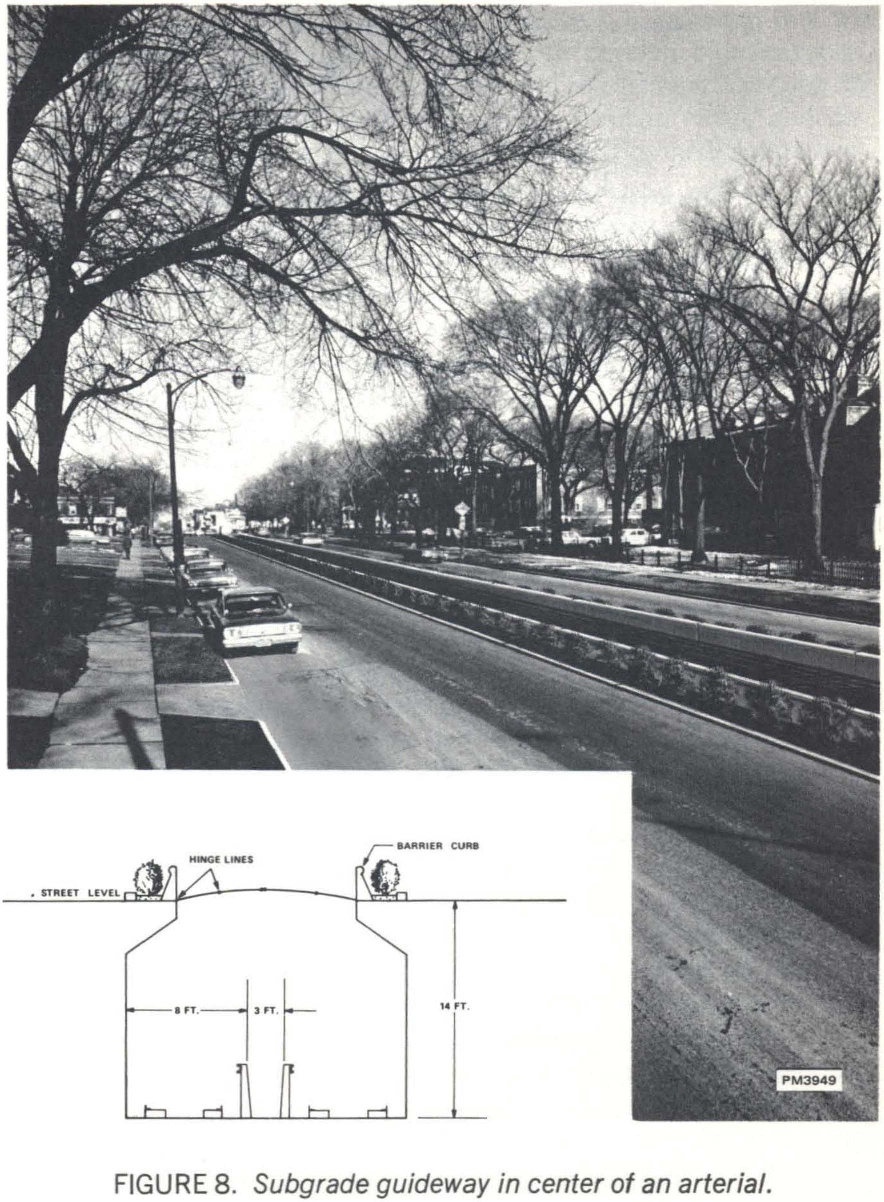


FIGURE 8. *Subgrade guideway in center of an arterial.*

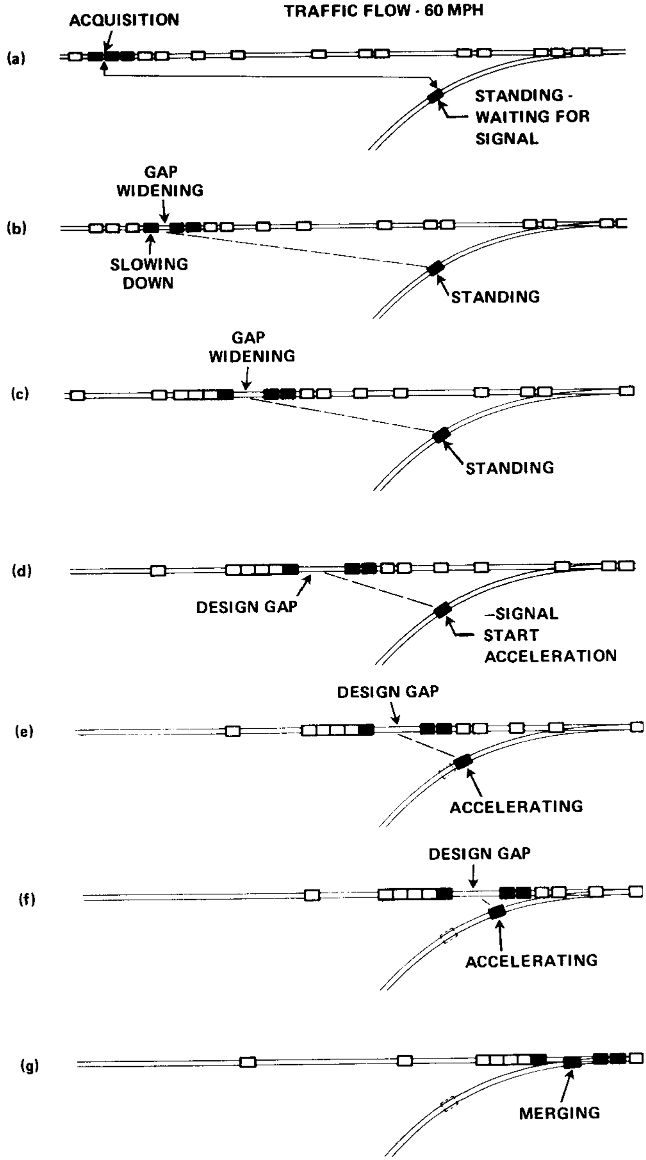


FIGURE 9. *Steps in the merge process.*

A system will include a number of types of stations and terminals. Most applications of dual-mode will require off-line stations to accommodate loading and unloading delays, because it is essential that the mainline be kept running at high speed, to develop high capacity. The off-line loading principle also allows "on demand" service by which a vehicle is called from an automatic parking ramp, and can be directed to a particular destination, bypassing intermediate stations.

Figure 10 is a schematic illustration of a large off-line station with loading platforms and a multi-storied automatic parking structure will handle non-private vehicles which can be stored and retrieved in serial order. The inner spoke-like arrangement of parking slots will handle private vehicles, as they require random access so that individuals may park and withdraw their vehicles at will.

Figure 11 shows a typical off-line passenger platform inside of a terminal. Note the safety fence and automatic gates. The Urbmobus is already loaded and the safety gate is closed.

Figure 12 illustrates a typical urban guideway network drawn to a city-size scale. The geometric layout is like an urban expressway in scale and pattern since it consists of radial guideways extending from the city core as well as several circumferential guideways to allow movement around the core and across the metro region. The network is superimposed over a street and highway grid (not shown) so that it can provide door-to-door service to a large region. The central loop skirts the city core and the outer belt is routed through the suburban fringes. Several large, line-end type stations are located in the core area and there are many small, off-line way stations to provide ready access to the street network. Note that the urban network interfaces with a high-speed, intercity guideway through a mode-mixer type of station. This suggests the apparent technical feasibility of using self-propelled vehicles on a national network of dual-mode guideways, which consists of urban segments operating at speeds of 60 mph and intercity links operating at about 100 mph, and that this system should be evaluated in any national transportation planning program.

It is likely that the vehicles traveling on these two elements will be different in size because of the differing requirements for speed, power, and comfort. However, the guideways will be identical so that higher speed vehicles can also travel in the urban networks.

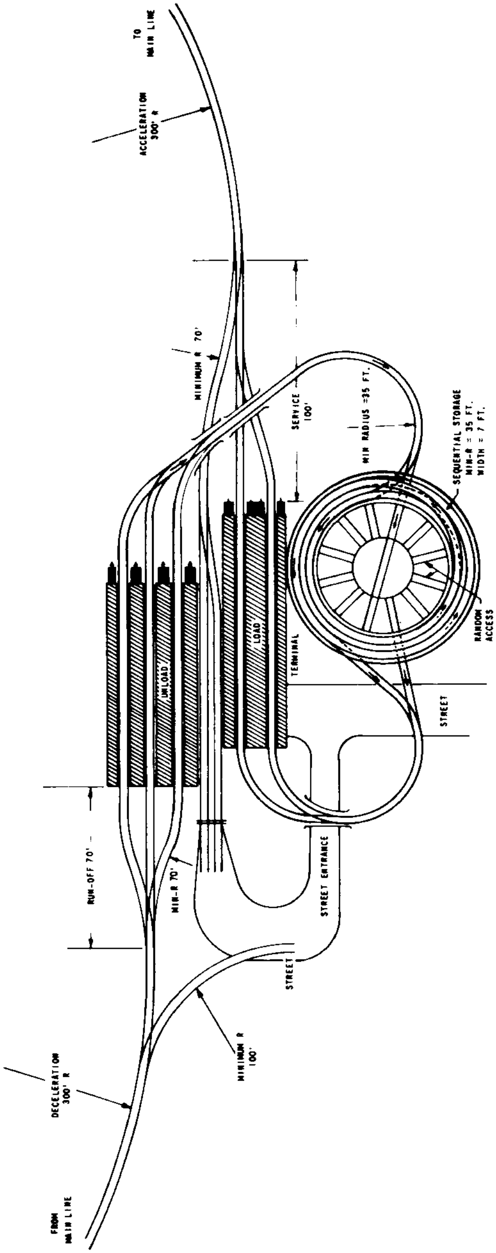


FIGURE 10. *Urbmobile terminal—generic design of total facility.*

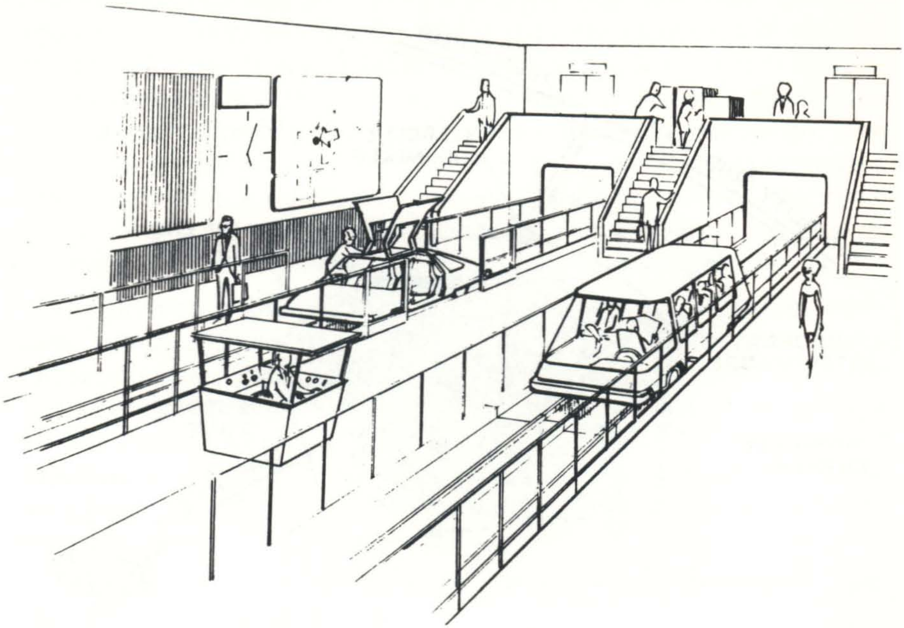


FIGURE 11. *Typical off-line platform.*

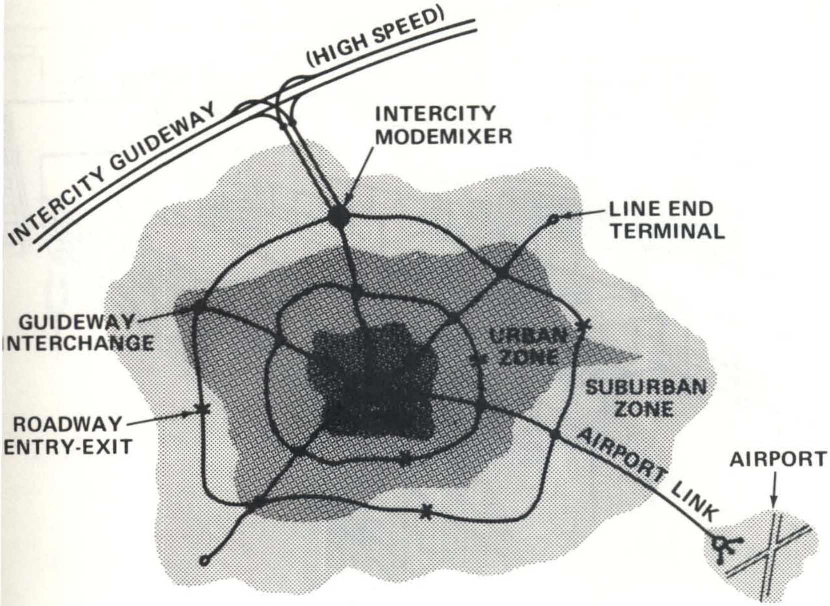


FIGURE 12. *Urban guideway network.*

Undoubtedly the greatest technical challenge in the dual-mode concept is the design and development of a practical, automatic guidance and control system which will safely manipulate thousands of vehicles operating in a guideway network. In defining the MK-I control system, we reviewed many automatic control concepts and finally rejected the "closed-loop" approach as being too complex for an initial design. The search for simplicity and reliability led to the "open-loop" synchronous longitudinal control scheme wherein there are practically no electronic control and servo systems in the vehicle, and individual vehicles on the main line are not directly controlled by a central computer.

The Urbmobile MK-I system (illustrated in Figure 13) requires three basic computerized subsystems. One performs a central traffic monitoring and routing function that "overlooks" and supervises the traffic in the whole guideway network and makes decisions as to whether certain main line routes and segments are open to entry or are saturated with traffic. Since it does not control individual vehicles on main line segments, its failure would not shut down the whole transportation system.

The other two computerized control functions, autonomous to local segments of the network, are

- An In-Terminal Subsystem which controls individual vehicles and general traffic in and near the terminal and includes the merge, gap control, and acceleration system, as well as loading, parking, on-demand retrieval, etc.
- An Enroute Emergency Shutdown Subsystem which detects and controls mishaps, and operates in the main-line guideway segments between stations and shuts down local groups of traffic to be shunted out of the nearest exit to clear the line.

It would prove too lengthy to discuss these in detail, but it is sufficent to say that automatic control is complex, needs further study, and that maximum reliability is essential to safe system operation.

To assist in the development of lightweight automatic transportation systems, we recently proposed to the U.S. Department of Transportation a "universal," instrumented test facility to be built at CAL and operated to serve government and industry in research and development of automatic "people mover" systems. Many of the basic features

CONTROL HIERARCHY	CONTROL FUNCTIONS
CENTRAL TRAFFIC SUPERVISORY COMPUTER	1. TOLL COMPUTATION AND BILLING OF "PRIVATELY-OWNED" VEHICLES 2. ACCESS CONTROL TO PREVENT "SATURATION" OF THE GUIDEWAY NETWORK 3. ASSIGNMENT AND RECALL OF VEHICLES FOR RANDOM ACCESS PARKING 4. ASSIGNMENT OF SYSTEM-OWNED VEHICLES TO MEET PASSENGER DEMANDS AT STATIONS
TERMINAL CONTROL COMPUTER	1. CONTROL OF VEHICLES ENTERING AND LEAVING STATION PLATFORMS 2. CONTROL OF GAP SENSING, GAP CREATION, ACCELERATION AND MERGE (OR ABORT) 3. CONTROL OF VEHICLES IN SERIAL STORAGE 4. CONTROL OF THIRD-RAIL POWER FOR EMERGENCY SHUT-DOWN 5. ADVISE CENTRAL TRAFFIC SUPERVISORY COMPUTER OF SHUT-DOWN
ENROUTE GUIDEWAY EMERGENCY SHUT-DOWN CONTROL	1. COMPUTE "TIME TABLE" FOR PASSAGE OF VEHICLES AT NOMINAL SPEED 2. DETECT PASSAGE OF VEHICLES IN OR OUT OF TIME "GATES" 3. REPORT TWO SUCCESSIVE "MISSES" OF TIME GATES TO TERMINAL CONTROL COMPUTER FOR EMERGENCY SHUT-DOWN

FIGURE 13. *Functions of computer subsystems.*

of generic dual-mode guideways and control systems would be incorporated into this facility. An artist's sketch provides a mini-system assembly described by Figure 14. In the foreground, we see a test vehicle ready to enter the system at the acceleration and merge ramp. It has engaged the third-rail electric power supply and is ready to accelerate under computer control. On the main-line loop, there is a string of approaching vehicles to simulate traffic. The computer will control them to provide a gap for the entering vehicle. If a malfunction occurs, the computer will operate an abort switch and the entering vehicle will be shunted onto the abort ramp where it comes to a controlled stop and can be readied for another entry test run. At the far side of the oval, there is an off-line station and control center, which incorporates an exit switch point, loading dock, and automatic parking, to provide "on-demand" vehicles. The station also houses the command and control center and the guideway instrumentation data readout console. A typical design of elevated guideway structure is also indicated.

To discuss safety problems in a comprehensive manner, it is helpful to mention some additional concepts in the dual-mode family. There are two other ideas in the dual-mode class worthy of introduction here; both are gradualistic in nature and competitive to the self-propelled version just described. There are many "electronic" or "automatic highway" concepts, favored by the automobile industry, wherein it is hoped that the contemporary automobile may gradually be converted to automatic control. The vehicles would be extremely complex, but it is argued that minor modifications or additions to our existing public roadway system would compensate for the vehicle's complexity. The second idea is that of using a powered pallet operating on a special guideway and capable of "piggybacking" conventional automobiles. The proponents of both of these concepts argue that adaptability to the present automobile, in a slow evolutionary manner, is the best way to introduce a new dual-mode system. As you probably suspect, I tend to disagree and would hope for a bolder approach, as I believe a true guideway is something much more than a converted roadway.

Since a considerable amount of technical study is being devoted to definition of guidance and control requirements for pallets, and the

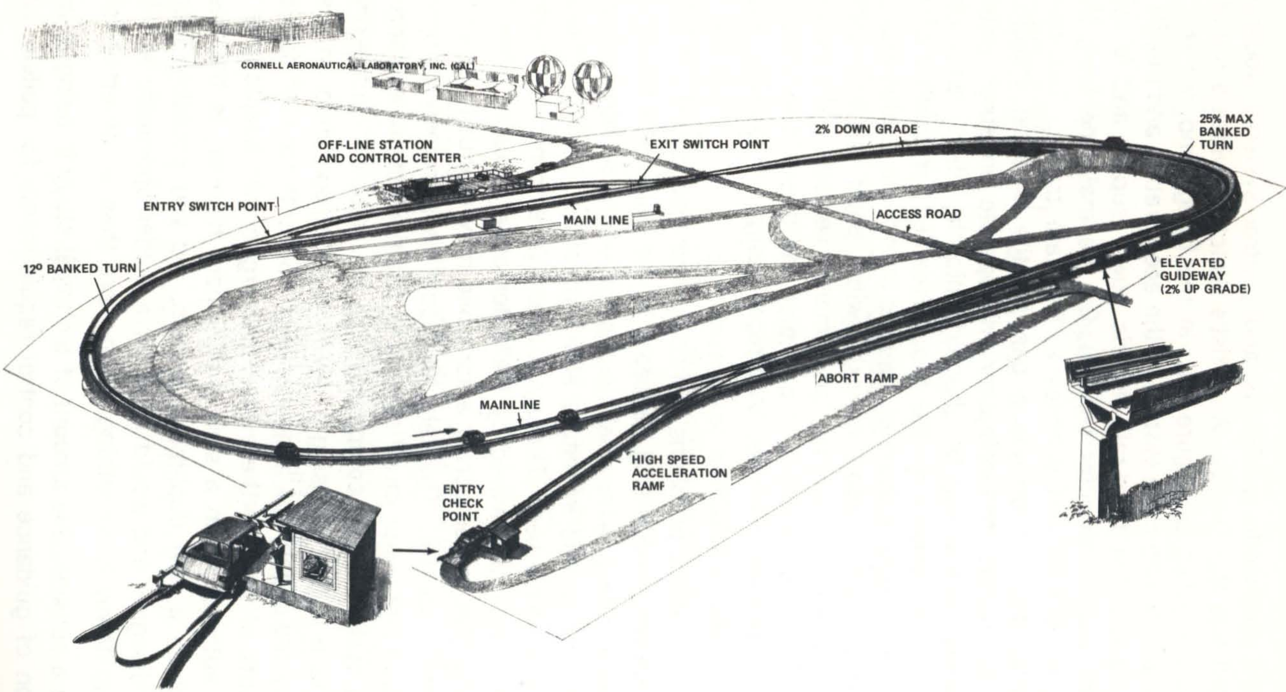


FIGURE 14. *Proposed CAL automatic guideway test facility.*

principles apply equally well to the guideway mode of dual-mode systems, a few illustrations of pallet configurations are included.

Figure 15 (center sketch of "Auto Carrier") shows an enclosed streamlined pallet-type vehicle intended to carry passenger cars. This early scheme, called GLIDEWAY, was outlined in 1965 by a team of MIT students working on a systems design project. It was intended that these vehicles be propelled by a linear induction motor built into the guideway.

Figure 16 shows a more recent version of an auto carrying pallet defined by a group of TRW systems engineers studying under a DOT contract (Boyd, Plotkin, and Tang, January 13, 1969). The huge pallet, designed to carry a 6500 lb. car at 150 mph, is 25 feet long, weighs 12,000 lbs., and uses 655 hp. Note that it is guided by flanged steel wheels, and therefore many of the control, braking, and adhesion problems, which will be discussed later, are similar to those of Urbmobile MK-I. However, as logical as the arguments of pallet proponents may be, it seems a shame to deliberately design a system wherein two vehicles are needed to do the job of one.

An Approach to Safety Analysis

The prospect of reaching line-haul capacities much greater than highways can achieve is one of the strong motivations for developing the dual-mode concept. In automatic systems, high carrying capacity is sought by using close vehicle spacing and higher average speeds.

Using small, personalized vehicles, one lane of guideway can "theoretically" handle as many passengers per hour as about 10 lanes of urban expressway. If urbmobuses were used, the main-line maximum passenger capacity would, of course, be even greater—reaching that of the big rail rapid transit systems. These high capacity goals are intimately connected with the issue of headway (the distance maintained between vehicles by the automatic control system).

Later, I will return to the question of "theoretical" guideway capacity versus "practical" capacity, because what is "practical" depends critically on what is "safe headway" as governed by social risk acceptance which, in turn, governs automatic control system design policy and equipment. Needless to say, a good safety policy is important, and,

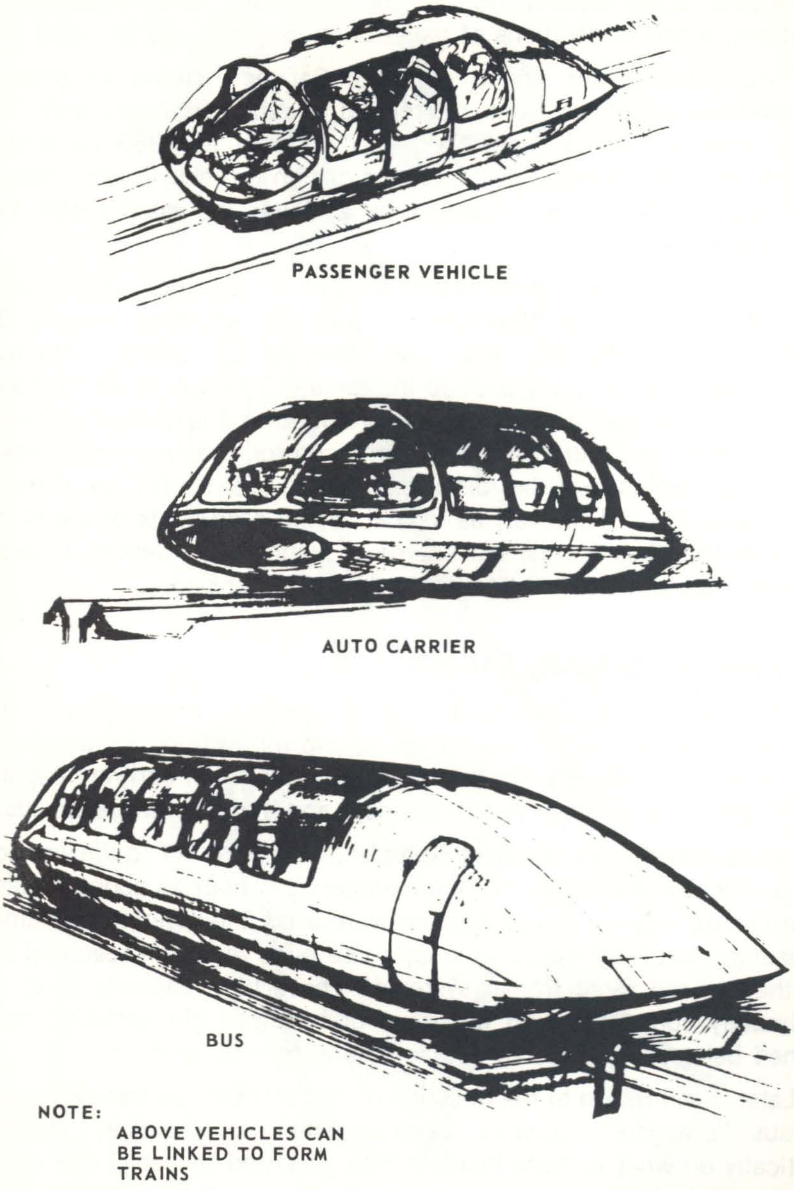


FIGURE 15. *Car carrying pallet (M.I.T. students).*

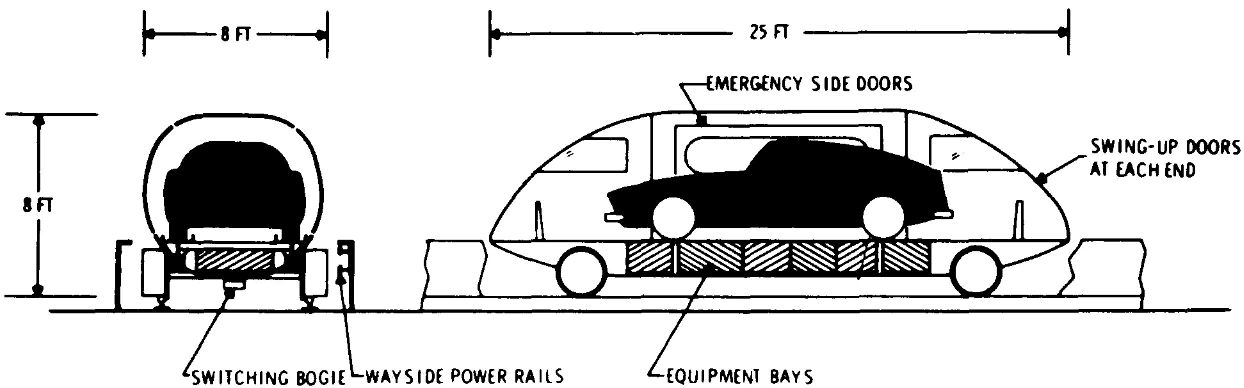


FIGURE 16. *Car carrying pallet (TRW Systems Group, 1969).*

when safety considerations are introduced, "practical" capacity becomes lower than "theoretical."

To reach the promised high capacities of the automatic mode, we must learn to develop automatic guidance and control systems which will allow vehicles to travel at better than expressway speeds, at closer spacings, and with greater safety; herein lies the great technical challenge.

It may seem a bit premature to discuss safety aspects of a yet unborn system, but "thinking one's way through" a new concept and anticipating problems, as well as solutions, is often a step toward realizing the successful implementation of the concept. In the conceptualization stage of new systems, prior to engineering design and physical experimentation, how does one identify safety problems? The answer to this question is complex and in some cases not easily attainable, but I shall present two basic approaches that I find useful.

1) One must first synthesize a complete, feasible system, including machines, equipment, human operating functions and system operational functions. Given the system, next try to imagine one's way through all of the functions and operations, with emphasis on safety to identify critical safety problem areas.

2) One can seek experience and precedent in the past history of similar existing systems and attempt to draw analogies relevant to the new system. Safety oriented operational practices, safety standards, and accident records reflect this experience.

Actually, a combination of the two approaches can be fruitful. In both cases, it requires a very broad and deep knowledge of the technical and operational functions of these systems. Since the great variety of skills needed usually do not reside in one person, some form of multidisciplinary team approach is needed to define the system and attempt to identify the safety problem areas.

Simulation of systems and analysis of their critical subsystems, with the aid of computers, has become a powerful tool to assist in this predictive process. Simulation models can, of course, be formulated to examine different problems and levels of complexity, varying from "software" examinations of gross control networks to detailed subsystems wherein characteristics of specific "hardware" are represented.

Reliability analysis has, in recent years, become a highly developed field, but so far I have not found a comprehensive reliability analysis of a dual-mode system concept, using modern methods of analysis. Even with its shortcomings, I would hope that such analyses would be forthcoming as an extremely imporant part of dual-mode research and development.

It has also become common practice in the space exploration program to utilize failure-mode analysis. Our national space program is an excellent example of how the process works—and also illustrates its fallibility through occurrence of certain accidents that are dramatic, but fortunately, not too frequent. Various forms of analysis are used in the early design phases to determine possible modes of failure and their effects on mission objectives and crew safety. This process can be applied effectively to our dual-mode design at the system, subsystem, and component levels. The primary objective is to identify critical failure areas, and suggest remedies to minimize risk. Analysis should express, if possible, potential failure in terms of probability of occurrence and seriousness of consequences. Typical considerations include need for redundancy, fail-safe design features and the need for more reliable materials, parts, devices, and components. In addition, this type of analysis can provide inputs to reliability models and can help establish safety requirements for the testing and operational trials which follow.

Let us remember that safety is, itself, a subjective social value, and the degree of risk that society will tolerate in a new transportation system relates in some way to the benefits, real or imagined, which these systems provide. Thus, in a transportation system development, safety is not an end in itself, but rather a desired attribute, important, but playing a secondary role to other values such as speed, convenience, cost, comfort, anti-pollution effects, and so on. We must also remember that there is no man-made transportation system that is completely safe. High-speed automatic systems, especially in their early developmental stages, will certainly produce some spectacular accidents; but airplanes, automobiles, and space ships did, and still do, produce these accidents.

Manual Mode Safety Problems

Let us first examine the anticipated safety problems of the manual, or street, mode. Drawing useful analogies from history and personal experience is relatively simple in this case. We are immersed in an automobile-dominated society, and once we have defined our new vehicles, direct comparisons can be made with familiar automobiles. We then have to extract only certain unique differences for further examination. An example is that for street use our new vehicle is an automobile, or bus but with two distinct differences that are listed below:

- The new vehicles are propelled on streets and highways by electric motors, drawing on self-contained electric energy sources such as batteries and fuel cells.
- The dual-mode vehicle has certain self-contained equipments and provisions, such as a retractable electric power pickup arm, electronic sensors and servos, and/or mechanical devices for guidance and control. These devices are built-in for adapting to an automatic guideway and must be disengaged when on the street.

What difference does the electric car pose in terms of safety? The National Highway Traffic Safety Administration, the federal agency charged with promulgation of highway vehicle safety standards, views its vehicle safety rule-making in three categories: *PRECRASH, CRASH, POSTCRASH* (National Highway Safety Bureau Motor Vehicles Program, 1970-1972). These categories provide a framework for discussion of problem areas anticipated for on-street safety of the electric car.

I can think of two ways in which the electric car might pose significant problems in safety; one is a performance deficiency, which I will call Trafficability, and the other is Crashworthiness. Performance deficiency of the electric car stems from the relatively poor performance of today's storage batteries. Crashworthiness problems may stem partly from the urgent need to keep structural weight at a minimum to overcome battery deficiency and partly from the newness of the art in design of efficient energy-absorbing structures that operate in the plastic deformation range.

Precrash Phase

Due to the lower energy and power densities of today's lead-acid storage batteries (compared with the internal combustion propulsion systems of contemporary automobiles), the first generation of marketable electric vehicles appearing in the U.S. will have acceleration and speed limitations which may create some problems of trafficability. This is manifested by questioning their ability to mix safely with traffic of higher performance vehicles, especially on expressways. Figure 17, drawn from a study of air pollution and the electric car, sponsored by the Department of Commerce, shows the ratings of specific power (watts/lb) and specific energy (watt hours/lb) for a variety of energy sources (U.S. Department of Commerce, December 1967). Here we see that the lead-acid cell has fairly good specific power (for short bursts), but its specific energy (a measure of range and endurance) is quite poor compared with some of the more exotic batteries and fuel cells. For those who wish to pursue this subject, you will also find Reference 7 of interest and utility. Figure 18 shows that if the plot of power and energy densities required of a typical 2000 lb. sub-compact car is superimposed on this graph, the intersection of the car and battery plots will provide range of about 50-75 miles at 20-30 mph, whereas the internal combustion power plant provides better than 200 miles range and speeds of more than 60 mph. A practical zinc-air battery would provide greatly improved speed and range.

This does not mean that all forms of lead-acid, battery-propelled cars are impractical, but rather that they are not yet competitive in performance with the familiar internal combustion passenger car.

One great advantage of the dual-mode electric car is that it does not need the competitive street range and endurance of the high-powered auto, because its high-speed trip is on the guideway where it is also charging its batteries. The guideway is thus a speed extender as well as a range extender.

Since it is well known (but not quantified) that "driver error" is a major source of highway accidents, and many people argue that vehicle handling characteristics are a contributing factor, we might ask: How will the electric car compare in this area?

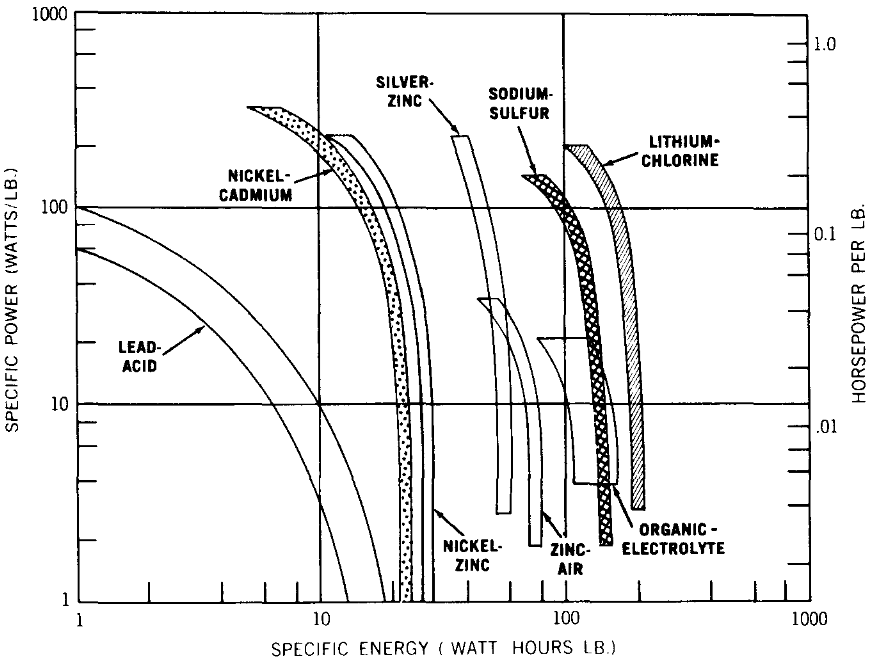


FIGURE 17. *Specific power versus specific energy for batteries.*

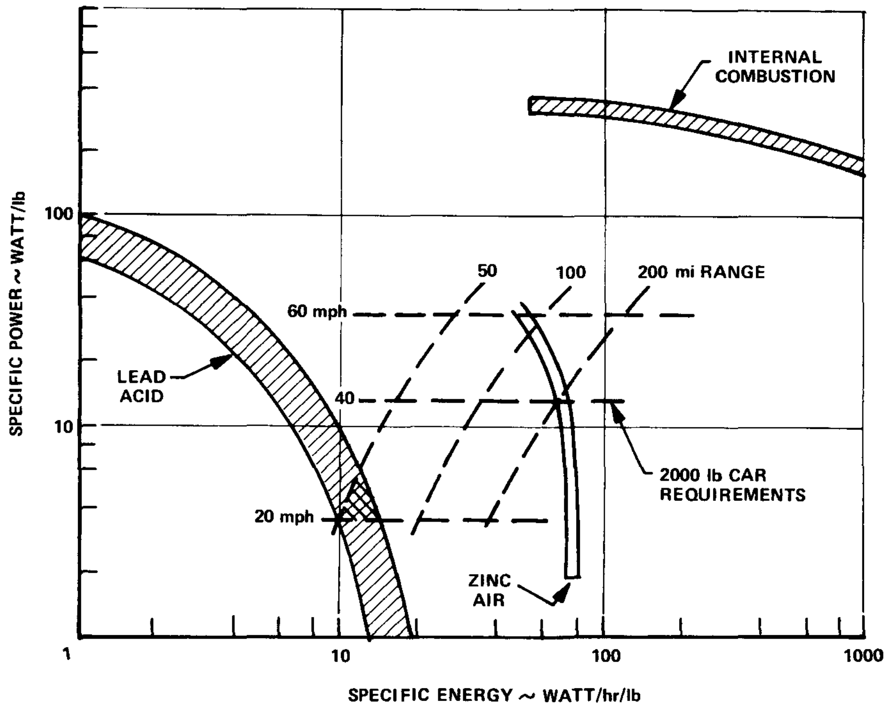


FIGURE 18. *Power sources and car requirements.*

My own limited experience with driving electric cars convinces me that handling can be adequate and a higher order of driving skill will not be required. However, the driver must adapt to the lesser performance characteristics of the electric car while he is discovering its idiosyncrasies during a transition period. During this phase of learning, he may be more prone to experience accidents than if he were operating his own powerful and familiar steed. Fortunately, the learning period may be relatively short and the electric car salesman might do well to provide a brief highway driver training course as part of his sales package. Many of you can remember your first experiences in mixing with high-speed expressway traffic with the early models of the Volkswagen. Here was a perfectly good little car, delightful to drive for a wide spectrum of driving situations; however, when mixing with big American cars at 65 mph, its passing and maximum speed capabilities were pressed too hard. One had to be very careful about hill climbing, passing distance, and maneuvering at these speeds. These problems have been corrected in subsequent generations of "Beetles" by improving "trafficability," i.e., by introducing better acceleration and high-speed performance by means of greater power density.

Thus, it will be with the first generation of roadable electrics—a matter of drivers adapting to low power and energy densities. We also can expect the second generation to have better performance, as better batteries are developed in the research laboratories.

With the strong regulatory forces at work in our society today there is apt to be a tendency to throttle innovation under the guise of safety. As you all know, the vehicle and driver relationships which may make a particular vehicle more or less prone to accidents are not well understood. Thus it appears to me that the most reasonable course of social and political action regarding the emergence of the electric car would be to adopt a national policy of tolerance. I would suggest that we let the new breed of vehicles hatch, but carefully monitor their early accident records to determine their "proneness" to accidents compared to conventional automobiles. It is my opinion that the problems of trafficability and accident causation, if they materialize at all, should be transitory.

Crash Phase

Although the electric car is not yet treated by Federal Motor Vehicle Safety standards, crashworthiness of electric cars and occupant protection from impact will rest on principles contained in evolving standards for conventional vehicles. These should not present problems differing greatly from those of the contemporary car. However, due to battery performance limitations, the electric car developer must seek minimum vehicle weight and optimum crashworthy structures. Further technical challenge will be posed because electric vehicles will tend to be small, thus requiring more ingenuity in structural design for impact energy absorption. In contrast to the abundance of predictive methodology available for structural design within the elastic range, we are faced with many blank spaces in the plastic range. Design in this region is still something of a "black art" and solutions must be reached by an iterative process of estimating and impact testing.

Battery packaging may present some special crashworthiness problems in an indirect way, but hazards, if any, will depend on the detailed design of battery installations and their containing structures. For example, in accidents, one might expect acid spillage, flying batteries, and short circuit, which might produce shock, explosion, or fire. There is very little experience with crash testing of electric cars, but our first tests at CAL in 1969 were surprisingly favorable (Cornell Aeronautical Laboratory, Inc., June 1969). Before the test, it was expected that the loosely attached batteries would tear loose under impact and that electrolyte splashing into the passenger compartment would be severe. The MARS II, crashed into an SAE solid barrier at 27 mph, had approximately 1,100 lbs. of lead-acid batteries distributed equally in the front baggage compartment and rear engine compartment. Electrolyte spillage from the front batteries was largely confined to areas forward of the dashboard and there were only a few drops of electrolyte which reached the face and clothes of the dummy and the passengers' seat area. All of the batteries in the forward compartment were found to have broken cases, undoubtedly absorbing some energy. The batteries in the rear compartment shifted somewhat, but all of them remained behind the rear compartment bulkhead, and electrolyte from the rear batteries was shielded from entering the passenger compartment.

Automatic Mode Safety Problem

The guided mode of operation, a less familiar area, presents problems that are new and challenging. In the following text, the anticipated problems of the guided mode will be examined.

When entering a guideway, the electric vehicle's operation is turned over to an automatic control system, and, in sequence, the following events occur:

- Destination is selected.
- External power and automatic guidance are engaged.
- If a slot is made available, the vehicle is accelerated and merged into a stream of fast-moving vehicles on the main line.

Once on the main line guideway, the automatic guidance and control system must function properly to (1) maintain speed and a safe distance between other vehicles, (2) eject the vehicle at a chosen destination, and (3) bring it safely to a stop in a station, parking ramp, or street entrance. The control system must also be ready and able to meet emergencies, avoid crashes and collisions due to malfunctioning equipment, loss of central power, or foreign objects on the guideway. Malicious vandalism must also be anticipated and counter-measured.

As suggested earlier, one approach to identification of safety problems is to examine system functions for possible hazard clues. The following partial listing of selected functions describes operation on the guideway and helps to identify potential failure modes. It is representative of a generic self-propelled, automatic guided vehicle, its guideway and its command control system. Each of these functions, related to hardware, software or operational procedures, is subject to failure; some with serious consequences, some trivial.

Guideway Entry Phase

- Automatic Vehicle Inspection
- Passenger loading (if from platform)

- Destination selection
- Guideway engagement (if from street)
  - guidance
  - power
- Acceleration and merge
  - traffic surveillance
  - traffic control and gap assignment
  - gap provision
  - switch operation
  - third-rail break and make
  - abort

<u>On-Line Travel</u>

- Third-rail power pickup
- Steering control
- Headway control
- Obstacle detection
- Emergency stopping
- Performance degradation detection
- Traffic control
- Occupant security
- Emergency passenger removal
- Emergency vehicle removal
- Maintenance personnel security

<u>Exit Phase</u>

- Destination selection
- In-vehicle switching
- Deceleration
- Third-rail break and make
- Re-engage power

- Exit disengagement (if to street)
- Switching (if to station)

In Station

- Switching (to loading platform)
- Switching (to automatic parking)
- Loading and unloading
- Emergency vehicle removal
- Emergency passenger removal
- Maintenance personnel security
- Collision avoidance
- Third-rail protection short circuit—shock
- Traffic control

Interchange

- A crossing interchange between two main lines is a special configuration of exit and deceleration ramps from one main line to entry of another main line using basic elements of guideway such as switches, ramp storage, gap control, traffic assignment, etc.

From the above listing of activities in the phases of merge, on-line travel, and in-station movement, an illustration of a major function is selected which appears to be a critical hazard area—on-line longitudinal control, lateral control, merge control and in-station operation. These should receive priority attention in all of the stages of development from preliminary engineering through reliability analysis, equipment development and quality control, to maintenance in day-to-day operations.

It is clear, therefore, that any guideway must be grade-separated from streets and highways and must be secure from intrusion. In addition, it must be weatherproof and operable in snow, sleet, rain and ice.

Another way to identify new safety problems is to seek existing precedent. A case in point would be grade-separated, turnpike tollway facility, having an entry gate, a "secure" right-of-way, one-way lane flow. This is somewhat analogous to the exclusive guideway of a dual-mode system except that there is manual control of vehicles on the turnpike rather than automatic guidance and control on the guideway. Many turnpikes also connect directly into urban expressway systems.

A review of the accident events which occur on the New York Thruway is revealing. The Thruway is a typical two-way intercity, tollway facility about 500 miles long, spanning the state (east-west), and it includes about 50 miles of urban expressway in the New York City, Buffalo, and Niagara Falls areas. It is subject to rain, snow, sleet, ice, fog, driver error, vehicle breakdown, and intrusion by people and animals. In a recent paper, advocating that highway engineers learn how to develop future manual intercity expressways with cruising speeds of 100 miles per hour, dubbed Century Expressways, I discussed the 1962 accident records of the Thruway (American Institute of Aeronautics and Astronautics, November 29, 1966). A portion of this record is presented in the lefthand column of Table 1.

Although there are differences in design and operation of the facility, one can anticipate some of the problems of limited access automatic guideways by reviewing the Thruway experience. Referring to Table 1, we see listed the types and numbers of accidents that occur annually. There is a surprising spectrum of accident types and two annual reports are included merely to indicate that these same events occur over and over, and tend to increase in frequency as traffic flow increases.

In scanning this list, it seems apparent that a large number of collision events are relevant, such as "head-on," "rear-end," "backing," "deer," "bird," "foreign object," "toll gate," "jackknife," and involve longitudinal collision, often without deviation from the traveled lane. Another class of events, such as "side swipe," "toll booth," "curb," "gas pump," "building," "center mall," "shoulder," involve lateral deviation from the traveled lane and are probably not quite so relevant to our discussion except in the case of steering system failure. Many of the above events are casually related to driver failure (control system in our case), while some are undoubtedly due to vehicle failure or roadway (guideway) characteristics.

Table 1

ACCIDENTS ON NEW YORK THRUWAY

By Primary Action	1962	1969
Collision		
Head-on	19	47
Rear End	959	1200
Side Swipe	354	556
Backing	27	72
Broadside	33	43
Flying Object	47	14
Fixed Object	11	17
Ran Into		
Traffic Control Device on Pavement	9	18
Small Animal	15	11
Deer	301	438
Large Animal	4	4
Pedestrian	14	22
Bird or Object in Motion	6	14
Foreign Object	63	144
Toll Booth Island	36	56
Closed Toll Gate	17	28
Curb	56	51
Gas Pump Island	4	7
Service Area Building	2	3
Barricade	7	18
Overhead Object	6	8
Other		
Hit Hole or Bump	12	2
Drove on Unstable Surface	1	1
Fire in Moving Vehicle	132	148
Overturned	42	67
Entered Center Mall	511	905
Person Fell from Vehicle	3	7
Entered Shoulder	957	1251
Vehicle Under Control, Left Pavement	11	16
Combination Jackknifed	43	110
Object Fell from Vehicle	26	153
Other Noncollision	10	11
Total	3738	5442

One would expect that with automatic longitudinal control replacing the driver, some of the longitudinal types of collisions such as "jackknife," "broadside," etc., would be avoided, though the mechanical control system is subject to failure and error. We also get some clues here concerning events which can definitely be expected to occur on guideways—even with greater security of the right of way. Foreign objects such as animals, pedestrians, maintenance personnel, falling objects, thrown objects and vandalism are bound to cause accidents.

So much for expressway precedent—now consider another source of clues. Railroad and rail-rapid transit operations have sired a large body of safety requirements, standards, and practices based on many years of experience. A review of the evolution of federal and private safety standards would be useful and one can procure such documents from the Federal Railroad Administration of DOT.

In the case of rail-guided, dual-mode systems, as proposed by CAL and Thompson, Ramo, Woolridge (TRW), and others, accident experience gained in railroad operations should be useful to alert the systems engineer to many potential hazards, other than collisions which he might not naturally anticipate. Derailment is a perennial problem stemming from many sources such as trackbed irregularities, wheel bearing seizure, foreign objects on track and even dynamic instabilities characteristic of bogies and their suspension systems.

It is interesting to note that major concern may not always be with passenger safety. Summary of the train and train service accidents, other than of grade crossings, prepared by the Public Utilities Commission of the State of California for the years 1965 and 1966, suggests that trespassers, rather than passengers, may be a more pressing problem. Table 2 shows that out of 160 fatalities, 141 were trespassers.

Longitudinal Control

One of the most direct clues derived from rail, rapid transit, and highway experience is the problem of headway policy. Headway is the maintained separating distance (sometimes expressed as time) between individual vehicles or trains when on the guideway. Minimum headways, which are required to achieve high capacity, are related to such factors as speed, vehicle length, braking power, and stopping

Table 2

RAILROAD ACCIDENT FATALITIES

California 1965-66

Passengers	2
Road Trainmen	5
Yard Trainmen	4
Motormen	1
Other Employees	4
Non-Trespassers	3
Trespassers	141
Total	160

distance. Over the years the railroads have established a practice of maintaining safe headways which in an emergency will prevent or mitigate severe collision with a leading vehicle that is stopped or stopping. There can be various policies based on accepting various levels of risk to passengers and/or property.

Several different headway policies and their implications to safety and line capacity for automatic pallet systems are discussed in a recent SAE paper by Boyd, Plotkin, and Tang (January 13, 1969).

The following list contains three policies that were considered:

1) Stopping distance. Used by railroads, in which headway must allow a following vehicle to stop safely if a leading vehicle stops instantaneously. This results in large headway requirements, hence low capacity.

2) Functional Train. Typical of freeways where headway is less than above but greater than the distance traveled during reaction time of a following vehicle. This results in no collision if the following vehicle decelerates at the same rate as the lead vehicle.

3) Light Collision. This policy is not formally approved by society but occurs on highways. Headway may be small to zero and vehicles may contact at low relative velocity.

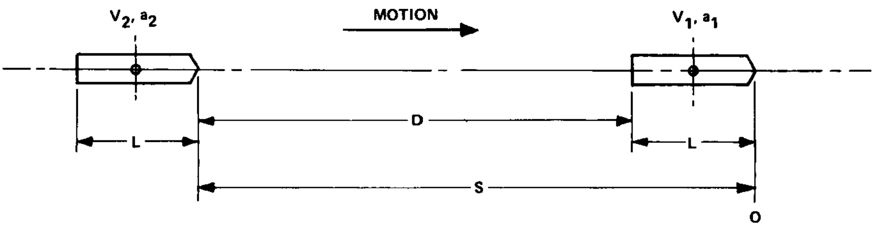
A major goal of dual-mode systems, when operating on the guideway, is to provide greater capacity per lane at higher speeds than urban expressways. Thus, the large headways demanded by the Stopping Distance Policy are ruled out here as being overly conservative for peak period capacity in an individualized small vehicle system.

The Light Collision Policy, although it may produce "ideal" capacities 8-10 times that of an expressway lane, admits the probability of frequent minor collisions. Weinberg (SAE, May 20, 1968), in his description of Urbmobile MK-I, used a modified form of the Light Collision Policy and open-loop synchronous control to achieve high capacity, as well as control system simplicity. With synchronous controlled speed, the expected relative velocity of impact would only be a few miles per hour. He proposed energy-absorbing bumpers on vehicles to reduce collision decelerations and "jerk" to tolerable levels. Such bumpers are being considered as standard requirements for future automobiles and would be of some advantage in any type of minor guideway collision. Even though this bumping effect is common on freeways and may be reduced to tolerable levels for emergencies on guideways, there is a question of whether the public would accept it for normal operations. The simplicity and reliability of the open-loop control concept is technically attractive, and the question of public acceptance of the risk in the Light Collision Policy should be evaluated and resolved as various dual-mode systems are explored.

If a more conservative approach must be accepted, this points toward the Functional Train Policy. This policy, although not always recognized formally by automobile drivers, is expressed in terms of "rules of the road" such as the familiar California Code.

Safe headway under the Functional Train Policy assumes that the same braking power is available to all vehicles in a string. This produces a braking process extremely sensitive to reaction time, i.e., the time required for a following vehicle to detect a "dangerous" deceleration in a leading vehicle and apply its brakes.

Figure 19 shows the headway and capacity relationships of the theoretical highway case, and assumes no vehicle position errors. For the automobile, this formula produces optimistic results because experience has shown that drivers do not behave according to theory,



D = HEADWAY (ft)
L = VEHICLE LENGTH (ft)
S = INITIAL POSITION RELATIVE TO REFERENCE LINE

CAPACITY, (WHEN V_1, V_2, α_1 α_2 ARE EQUAL)

$$U = \beta\left(\frac{5280}{L} - \frac{5280\,\beta}{L\,(\beta + V_o)}\right)$$

U = VEHICLES/hr/LANE(mph)

V_o = INITIAL VELOCITY (mph)

$= \frac{L}{1.467\,J}$ mph/VEHICLE LENGTH OF SPACING

$D = \frac{L}{1.467}\left(\frac{1}{V_o} + \frac{1}{\beta}\right)$ sec, OR $1.467\ V_o\ J$ (ft)

J = BRAKING REACTION TIME (sec)

FIGURE 19. *Capacity and headway relationships.*

but they become nervous and slow down as flow increases, so that practical maximum capacities for freeways occur at 40-45 mph and at 1800-2000 vehicles/hr. In any case, based on the above geometry, and assuming that initial velocities and decelerations are equal, the capacity for the Functional Train Policy may be computed for the dual-mode system.

This is a steady-state condition and does not allow for transient vehicle position errors due to sensing, control system, or vehicle response characteristics. In depth study of control error effects must come later, but that detail is beyond the scope of this paper. The effect of control system error, however, can be illustrated by the simple expedient of representing a "virtual length," or "slot," which the vehicle could occupy if it had a position error defined as a fraction of its length.

Assuming that this error is $\pm$ 1/4 L, then the "virtual L" is 1.5 x "actual L" of the vehicle.

Figure 20 is a plot of capacity vs speed for various systems. The dotted curve is a typical, actual expressway performance curve showing that maximum lane capacity occurs at about 40 mph and drops off as speed increases. The curve just above it is the theoretical expressway capacity under the California Code, using a braking reaction time of 1.16 seconds.

The two upper curves are for dual-mode systems with an assumed reaction time of .25 sec which is considered feasible for an automatic system that detects a specified "dangerous" deceleration threshold and applies the brakes. Both curves are for 12 feet long vehicles. The uppermost one assumes no position errors, while the lower one contains the effect of error of $\pm$1/4 L.

This pair of curves should tend to "bracket" the expected performance of small dual-mode vehicles under the Functional Train Policy. If we consider 60 mph as a nominal guideway velocity for dual-mode, its lane capacity of about 8000 vehicles/hr is approximately 8 times that of the typical expressway at that speed. Passenger capacity depends on the occupancy per vehicle.

Insight regarding the effects of speed, vehicle size, and payoffs of reaction time can be gained by "reading between the curves" of this

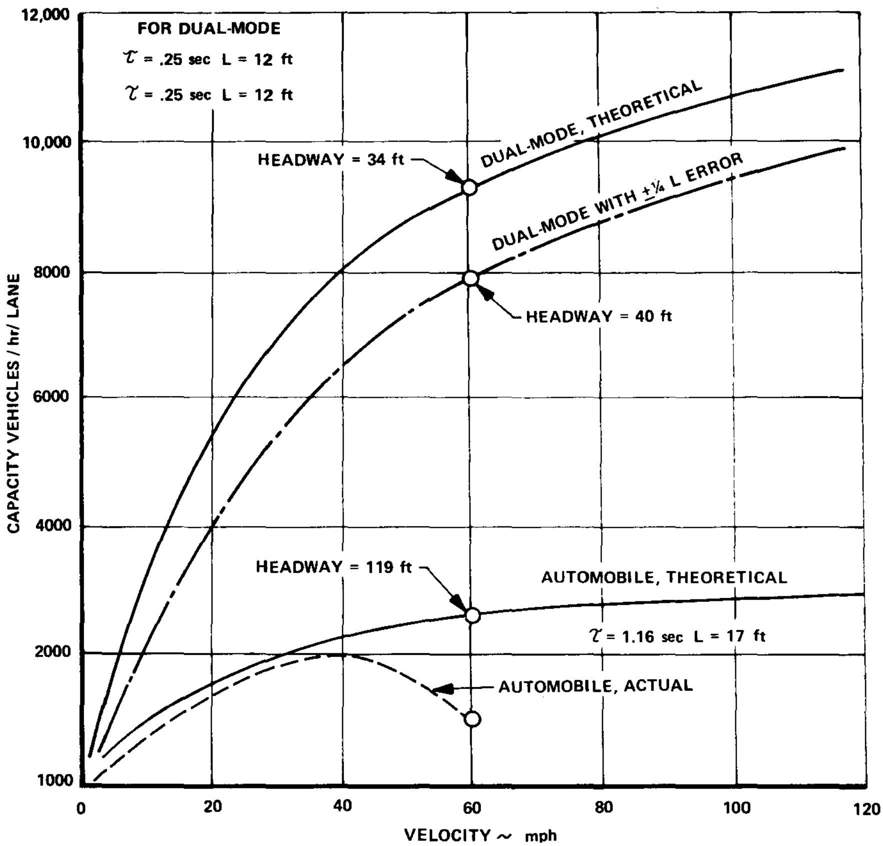


FIGURE 20. *Capacity ~ "functional train" policy.*

graph. For example, one might guess that a 24-foot urbmobus might, at 60 mph, indicate about 4000-5000 vehicles/hr as maximum capacity, which could mean 30,000-50,000 people per hour at peak. This, of course, may be readily computed from the formula, assuming various passenger load factors.

Headways at 60 mph are shown by the circles, intersecting the theoretical capacity curves, and are repeated in the table below. Note that as headway decreases, capacity increases.

Theoretical Headway		Capacity (v/hr)
Automobile	119 ft	1000
Dual-Mode (with error)	40 ft	7900
Dual-Mode (no error)	34 ft	9300

We can conclude that on-line capacity of any automatic longitudinal control system must be determined by headway policy in combination with specific control errors characteristic of each type of guideway, vehicle, and control system design. General statements about dual-mode system capacity must be viewed with caution until a number of specific, practical control systems are designed and evaluated.

There are some ways of alleviating the risks of close headway. An intriguing example of one way this may be done is the idea of using different headway policies on different segments of a guideway network to increase average system safety as traffic demand varies throughout the day. This plan certainly seems to be within the capabilities of modern computerized traffic control.

The following question summarizes the problem of safety in emergency stopping. Can technology produce a reliable automatic control system for close headway operations that will provide effective emergency braking under all weather conditions? The answer is not solely concerned with friction, electronics and computers, but also depends on the level of risk which society will tolerate to gain the benefits of this new system.

Lateral Control

In addition to the problems, anticipated and existing, connected with longitudinal control, problems of steering and lateral motions must be considered. Herein lie the side resistance forces that must be available to maintain control of the dual-mode vehicle. I have certain reservations about the all-weather capability of rubber-tired vehicles operating on concrete, or similar running surfaces, under "free control," which depends solely on electronic guidance. Vehicle position provided by radiating sources, such as a guide wire buried in the roadway, or mounted along the roadside, have no mechanical tie with the roadway. The "free" schemes rely on in-vehicle sensing and servo steering systems which obtain their position fixes from an in-road or roadside reference system. A basic hazard is present on icy surfaces, caused by reduction of the coefficient of friction between rubber and icy concrete to negligible or very low values. This results in loss of the side force capability needed for steering. The control problem is compounded by the fact that ice usually occurs in random patches that cause jerky vehicle response, even if violent skidding is avoided. There is also the problem of sudden front tire failure which may cause lateral deviations beyond the corrective power of the guidance system.

The problem may be stated as follows: Given rubber tires and icy roadways, an automatic control steering command may not be able to produce the desired steering response because the tire adhesion (side force capability) is so poor that the vehicle cannot respond properly and it loses its guidance. This problem provides us with the major nemesis of early electronic highway concepts.

There are various solutions which provide a mechanical tie to the guideway, capable of resisting sideward motion. Most of them, however, add complexity to the system. The flanged steel wheel, chosen for Urbmobile MK-I, is one of the simplest and most reliable solutions. Most other solutions involve extra sets of side wheels or air bearings, pressing against walls, side rails, I-beams or other relatively solid restraining structures.

System Entry and Merge

To reach high capacity is an imperative goal of dual-mode guideway operation in that the main-line traffic must be able to keep moving at a relatively high average velocity and at short headways. This requirement leads to the off-line station principle, so that vehicles may enter the system from the street or stop at loading platforms without interference with main-line traffic flows. The off-line station concept, combined with parking docks, or ramps, also allows individual on-demand service not possible in the usual rapid transit system.

Regardless of whether a vehicle enters the guideway system from the street, a loading dock, or parking facility within a terminal, it eventually reaches a point at a guideway entry ramp where it "engages," or "locks," into the guideway system and awaits a "go" signal to accelerate and merge into a suitable gap. Queuing is certain to occur at entry points as vehicles await clearance for assigned "open" pathways to their desired destinations. Various entry policies such as "first-come, first-served" or "first open pathway" to destination, and so on, must be established for the assignment programs of the computer. Gap assignment, start command the velocity control profile along the ramp, as well as a provided gap, must be so managed by a computerized control system that the vehicle seeks a safe merge with the moving gap. It seems quite obvious that failure, or malfunction, of this gap and merge control subsystem can be identified as one of the major hazardous points in the total system design, because collisions could be catastrophic.

Thus, design and development of an automatic control system that safely manages thousands of vehicles in the main-line guideway network and still provides safe gaps at many entry ramps, without delay, is a major and challenging technical problem, and advocates of this system maintain that this procedure can be achieved more effectively with automatic control than with manual control.

An analogy to the familiar expressway duel between merging driver and on-line driver may serve to illustrate the nature of the automatic control functions required. Under conditions of light traffic flow the duel is essentially a two-person game and there is no difficulty with the merge. Headways are large and gaps are easily created as the main-line driver has two degrees of control freedom—longitudinal and lateral. The merging driver can adjust his speed on the ramp in a continuously adaptive fashion to merge with the slot. In an emergency he can even come to a stop, or pull off onto the shoulder.

However, when main-line flow is dense and the entry ramp is crowded, the gap creation problem becomes more acute for both on-line drivers and entering drivers. Now, both drivers are operating in relation to their own segment of guideway traffic, as well as "computing" the gap locations. The on-line vehicle is traveling in a group of close-packed, fast-moving, aggressive drivers and every move the driver makes to provide a gap must be cautious and hesitant and is reflected in reactions by his neighbors. This produces much individual "jockeying," resulting in a telescoping or shock wave effort in the main line which may travel large distances back. The driver on the ramp may have similar problems, and the usual result is that, because of the driver-to-driver uncertainties, the main line traffic slows down, the entry ramp jams, and once-in-a-while a polite and confident main-liner, at the risk of a bump in the rear, manages to open a gap for a merging car.

There are two widely divergent schools of thought on the basic approaches to managing this situation by automatic control. One school maintains that it should be done with some sort of centralized command and control system which knows the instantaneous position of all vehicles in the guideway system, and controls them accordingly, while the second school says do it with an autonomous control subsystem which essentially ignores traffic outside the range of influence of the local entry-exit area. In other words, who at exit 29 cares what traffic is doing at exit 49, twenty miles away? After presenting these two approaches, it is quite obvious that the first scheme is very complex, while the second presents an oversimplified view of the problem. Somewhere between these extremes, there must exist and we intend to find, tractable solutions.

There are many possible traffic management and merge control schemes, some already outlined by interested control systems engineers that may, along with additional ideas, provide the ultimate solution to the problem.

Weinberg worked out CAL's first merge control logic in 1965 and this was later expanded in the Urbmobile study for HUD (Cornell Aeronautical Laboratory, Inc., March 1968). He and his colleagues had chosen the concept of autonomous, fine-grained block control near entrances, exits and stations, coupled with open-loop control on main-line links. This allows a simple central traffic monitor subsystem which would observe gross traffic flow throughout the network and allocate entry priorities to avoid system saturation. In this case, the computerized traffic monitor need not sense and account for instantaneous vehicle position of all vehicles in the network, nor does it need to control individual vehicles. Preliminary control logics and computer requirements for the local gap and merge control subsystem were worked out for the case where an advanced gap is provided. The concept of an abort switch located in the acceleration ramp just ahead of the mainline switch point, and a return guideway loop for a "second try" in the event of correctable malfunction, were also identifed as needed safety measures.

Cunningham and Hinman recently simulated several merge control logics utilizing linear control theory, including errors (Cunningham and Hinman, October 1970). They examined the problems of merging into a four-vehicle string traveling at 50 mph under conditions of (a) an advanced gap provision logic, and (b) a random approach of a merging car. The advanced gap scheme worked quite well without violent braking or acceleration demands. The random approach, however, required excessive braking of on-line cars to allow a merge. A possible solution, however, is to provide about 250 feet of parallel track before the merge point, for vehicle adjustments.

Several other investigators working with Boyd, of TRW Systems Group, under contract with the U.S. Department of Transportation, have published control system studies related to synchronous longitudinal guidance and control (TRW Systems Group, September 1969). This work described various control policies and formulated control algorithms to optimize capacity with safety. A small network, including entry assignment, gap provision, route assignment and on-line control functions, was simulated and various control algorithms were explored. Capacity, as influenced by control system parameters and speed, was also investigated. Thus, the study extends into an intercity speed range and concludes that, with advanced equipment and proper control system design, capacities of 7400 vehicles/lane/hour could be achieved with 18-foot vehicles traveling at speeds in the 125-150 mph range. This helps to confirm CAL's original speculation that high-speed intercity guideways are feasible. It also lends realism to the concept that future regional dual-mode systems may consist of slower-speed urban networks connected by compatible high-speed intercity links. The study also specifies a "deterministic" longitudinal control system wherein position of all vehicles in the system is accountable at all times. This demands a very complex closed-loop central traffic control system, or many segmentalized but coordinated subsystems, as compared to Weinberg's simple open-loop synchronous approach.

The serious student of automatic transit and "people mover" systems is advised to study the series of system descriptions compiled by the Applied Physics Laboratory of The Johns Hopkins University (The Johns Hopkins University, 1970). Ten contemporary single-mode transportation systems and a variety of guideway and control concepts are described. Understanding of their performance goals and design features lend perspective to this discussion on safety problems.

These various schools of thought regarding headway policy and control system complexity must be carefully studied and weighed before exposing the public to riding on high-speed, automatic guideways. Undoubtedly it will require a good amount of technical development, as well as a sociological evaluation of the risk acceptance necessary to achieve workable solutions.

In-Station Safety

Previously, we have mentioned the need for off-line stations and terminals, but have not discussed the safety aspects of these facilities, which are appropriate to our inquiry.

We have made the point that the off-line station is an essential component of the guideway, necessary to allow loading and unloading, at leisure, while the main line keeps flowing. The simplest type of off-line station would not admit entry or exit from the street, but it would have a main-line exit switch, deceleration ramp, loading platform, storage dock, guideway entrance and engagement spur, acceleration ramp, abort switch and main-line entry switch. In addition, there would be safety fences, gates, ticketing devices and certain security features, such as a TV surveillance and public address systems, linked to the system control center. A major terminal, however, would have all of the above elements plus provisions for automatic parking, entry and exit from street, and vehicle inspection and maintenance.

Within a major station complex, there will be a lot of maneuvering and the speeds will be much lower than on the main line. Because of this, collisions will not be so calamitous, although they could disrupt, or temporarily stop, in-station service. Minor collision damage, although not hazardous to passengers, could upset guidance, control, or power systems. A big station will also have many switch points to channel vehicles into the various functional subsystems, such as loading platforms, parking facilities, maintenance docks, and street ramps. The station must also be carefully designed with safety gates and warning devices to prevent passenger accidents at loading and unloading platforms. Preventive measures must also be taken to keep people from falling onto tracks, being electrocuted by the third rail, and so on.

The complexity and amount of in-station equipment suggests that skilled maintenance personnel will be required in large numbers.

This fact should appease union opponents of the system, who oppose the encroachment of automation, but it also suggests that maintenance personnel may be especially subject to accidents. This possibility presents a further safety consideration that must be dealt with when implementing an automatic system of transportation.

CONCLUDING REMARKS

It is my feeling that we have presented a good technical case for implementation of the Dual-Mode transportation concept. Discussed were the feasibility of the system, its challenges, both technically and from safety aspects, and the need for federal leadership to attain a universal, standardized transportation guideway network. Realistically, I feel that these questions can be dealt with by using the research tools of analysis, experiments, and development, as well as by educating the public as to the benefits and risks of this system.

A few sociological ramifications of the system were also briefly considered. In this area, further treatment is needed because these complexities may present a significant challenge to the ultimate implementation of the Dual-Mode system. My feeling is that the complexity of the societal viewpoint, in general, may resist such a broad deviation from the accustomed mode of automobile transportation. Therefore, it is not enough to have the research ability to technically create an automatic transportation system; there must also be simultaneous sociological research undertaken to ensure that "cultural lag" will not cause its rejection.

In conclusion, then, we see the Dual-Mode transportation system becoming a reality through a "Dual-Mode" of research, namely, technical and sociological.

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DISCUSSION

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The concept of dual-mode transportation is both fascinating and challenging. Our speaker, Mr. Wolf, has elegantly described many of the advantages and disadvantages of The Guideway System, the urbmobile and other dual mode transportation systems. In comparison, he has discussed the advantages and disadvantages of the door-to-door conveniences of the automobile.

We've had the automobile a long while, largely because it has provided a convenience of service that has been difficult to surpass. Yes, it's an expensive mode of transportation, but to date the public has been willing to pay its cost for the convenience offered.

Personally, I have a strong preference for some concept of dual mode transportation as described by our speaker. However, my optimism wavers when I study the man portion of the man-machine-environment system applicable to transportation. Man doesn't follow the herd like a cow, nor the tide like a fish, nor the wind like a bird. Man is the only animal that uses a mechanical device or artificial means to transport himself. Dogs still walk, they don't build dog cars and drive them. Man is different in that he has strived, and I think will continue to strive, to direct his own destiny, including motion—his transportation. He insists upon moving faster and farther than his legs will carry him, and inherently he desires to guide himself.

Now we speak of the feasibility of high-speed fixed ground transportation, dual mode vehicles, public transportation, etc. The movement of people as transportation is really a means of communication—physical communication, and I think technological developments, particularly in the field of visual communications and visual communications linked with computerized ordering, etc., will have a dramatic effect during the next two decades upon what we now consider the purposes and needs of transportation. Whereas some ninety percent of our trips now occur on less than ten percent of our highways and streets, and cover less than ten miles, I think a large portion of these short, frequent trips will be replaced by more sophisticated communications in the future.

Then wherein lies the future of transportation? Along major corridors such as the Northeast Washington to Boston and New York to Chicago, and lesser corridors such as Raleigh to Greensboro to Charlotte, there will develop sufficient travel demand not only to justify, but to require some type of frequent high-speed ground transportation. The technology has yet to be refined for us. But the demand will come about, as the following illustrates: A high-speed fixed-line system may carry up to 60,000 persons per hour whereas with an auto averaging 1.5 persons per vehicle and 1000 autos per lane per hour, it would require 40 lanes of superhighways running to capacity to move the equivalent number of persons.

Now the theme of this symposium is highway safety, and I maintain that we surely could have some safety problems if we had 40 lanes of superhighway running full to capacity across the state, particularly with a light snow falling.

Of course, the key to this illustration is that fixed-line high capacity transportation has a tremendous offering, provided there is a demand for its use. Here is where we need to plan ahead. We have seen and are continuing to see the rapid growth of the Carolina Piedmont Crescent as an urbanized area. Yet, you can study air photos along this corridor and find a path from Raleigh to Durham to Burlington to Greensboro to Winston-Salem and to Charlotte that is either open farm land or woodland and completely undeveloped. I ask you, will we still be able to find that corridor by the year 2000 or will we be taking pictures of more broken bodies and vehicles trying to crowd the way along the highway?

Now, in all honesty, I must revert myself and defend the automobile—the plain drive-it-yourself automobile. There will continue to be a pressing demand for the use of the automobile. The convenience of reaching the front door, the flexibility of routing where you desire, the convenience of changing your route while enroute, the privilege of privacy and selection of companionship and the inherent pride of being your own master and driver will not be brushed aside. No, transportation systems will become a dual mode—one being for speed and efficiency along selected corridors of high demand and the other being for the meandering convenience of the automobile. I think there will be separate and distinct systems and we will continue to be faced with the problem of highway safety.

A few final comments on highway safety. We're being bombarded with accusations that vehicles have safety defects, highways are designed poorly, and all drivers are drunks. As I stated earlier, it is a man-machine-environment system. We can blame the vehicle all we want to and we can blame the highway and the environment all we want to, but man does supposedly have a superior mind and capability. He buys the vehicle, he maintains it, he drives it, he can see the road (the road can't see him). So why isn't the driver the most responsible aspect of the system?

Man's talents and capabilities are enormous in most respects. He can build airplanes that fly faster than sound, travel to the moon, build gigantic buildings, perform delicate operations, write beautiful poetry, paint works of art; yet often he can't safely drive an automobile. Herein lies the challenge: Highway deaths and injuries will not be signifcantly reduced until man, the driver, is made to recognize the significance and importance of his role in controlling the vehicle for a varying environment.

Section II

Visual Acquisition of Information in Driving Through Eye-Movement Techniques: An Overview

Thomas H. Rockwell

Discussant

Stephen R. Schroeder

THOMAS H. ROCKWELL

Dr. Rockwell has been at Ohio State University since he went there to pursue his Master of Science degree in the early 1950's. A faculty member since 1955, he received his Ph.D. in 1957 in Industrial Engineering. He is currently a professor in the Department of Industrial Engineering and serves as director of the Driving Research Laboratory.

His work covers a wide range of activities, including risk acceptance in man-machine systems, evaluation of driver education curriculum, systems performance in light aircraft control, evaluation of highway signing, and the use of electronic guidance devices for traffic safety and flow.

Perhaps of even greater long range significance is the fact that Dr. Rockwell involves graduate students in his research activities, so that he is preparing and encouraging young people to enter the field.

VISUAL ACQUISITION OF INFORMATION IN DRIVING THROUGH EYE-MOVEMENT TECHNIQUES: AN OVERVIEW

By Thomas H. Rockwell

For years researchers in human factors have attempted to define the driving task and to ascertain the elements of the driving control process in order to develop an understanding of human vehicular control. This understanding is imperative if we hope to better design vehicles and highways around the capabilities and limitations of drivers and to better train drivers themselves to effect safer and smoother flow on our highways. The problem has been a difficult one because the input side of the process has been largely unknown. We have attempted to describe optimum vehicular control techniques without knowing the information acquisition aspects of the task. General conceptualizations, such as information theory and servo theory, have not been altogether convincing because of our lack of knowledge about the information needs and information acquisition characteristics of the driver. Since driving information acquisition is largely a visual process, it was apparent that this sensory mechanism first demanded quantification and analysis.

Several years ago the techniques in eye movement research began to be applied to the driving task and results, while still exploratory, suggest a new area of research investigation with exciting potential. It is the purpose of this paper to describe these initial efforts at mapping the driver's visual information acquisition process, hypothesize on the significance of early research results and point out the challenges ahead to the researcher.

The role of vision in driving is believed to constitute over 90 percent of information input to the driver. Regardless of the exact percentage, without a doubt, visual perception is paramount in vehicular control. Unlike motor output, perception is very sensitive to changes in the roadway environment, vehicular design and particularly to changes in the driver's psychological and physiological state at any given time. Visual processes can be degraded by glare, fog, lack of illumination in the environment, by vehicular design (in terms of tinted glass windshields or "A" pillar location), and by such factors as alcohol, fatigue, and drug usage.

It is evident that visual information acquisition failure due to sampling the wrong information, the right information at the wrong time, or failure to sample at all are far more related to accident causation than motor processes failure or control failure. Rear-end collisions and run-off-road accidents, two of the most common accidents found today, clearly suggest the failure of the visual information sampling process and subsequent information processing.

Understanding the processing of information of course does not necessarily follow from research in eye movements. Indeed, eye-movement technique can only tell us what information is available to the driver. Whether he intends to use a fixation to process particular information or whether it is utilized now or at a later time through short-term memory processes is beyond our present capability. Regardless of hypotheses about these issues, it is possible to at least ascertain from eye movements that information available to the driver which is *not* sampled. More importantly we can, as will be seen later, study intra-subject sampling as a function of learning, familiarity, fatigue, alcohol, and different driving tasks.

Eye-Movement Technique

Eye-movement technique essentially permits determination of foveal fixations in time and space, recording voluntary and/or involuntary saccades. Drift or tremors of the eye are too small and too short in duration to be captured with the equipment to be described. Pursuit eye movements, however, can be detected and represent one of the unique characteristics of the fatigued driver. Eye movements can also be characterized by movement distance and duration. Most eye movements in driving are less than six degrees travel and most eye fixations are between 100 milliseconds and 350 milliseconds in duration. In driving we can further determine that some 90 percent of the observed fixations fall in a small region, within plus or minus four degrees from the focus of expansion.

The earliest measurement technique used in aircraft instrument flight operation to record instrument sampling, involved direct photographs of the eye. This method is not too accurate and is not useful if the scene objects change their position in time as with automobile driving. Direct photo-electric methods which measure contrast differences of the sclera and the iris are useful but suffer in vertical accuracy. We use such a system for laboratory confirmation tests of road studies. Mechanical cups or mirrors fastened to the anesthetized eyeball are found in precise laboratory research but not in the harsh realities of the actual driving situation.

The system used at the Ohio State University involves both video and 16 mm motion picture processing and operates on the corneal reflection technique. See Figures 1 and 2. With this method a small focused point of light is reflected off the cornea back into a collecting lens and recorded on film or tape. The proper calibration of normal eyes permits accuracies of ± one degree vertically and ± one-half degree horizontally. Subjects must have reasonably round corneas to get a small eyespot. Range of eye travel for useful calibration is ± 10° from line of sight. Subjects must also not suffer from amblyopic problems.

The key to good and accurate eye-movement research technique is stabilization of the eye source relative to the position of the eye. Figures 3a and 3b show the stabilization helmet and equipment in the car. This consists of an upper dental bite bar and a helmet cast to the shape of the individual subject's head. Frequent recalibration is essential if this system is to yield consistently accurate data. Calibration can be checked at the beam splitter or with the TV monitor by having the subject scan certain targets in the visual field, for example, taillights, signs, etc. The latest system in use at Ohio State University is shown in Figure 4. The system has 50° x 40° field of view and uses only one fiber optic cable to transmit the corneal reflection. The system has a third vidicon that photographs the eye directly to record mirror and speedometer usage when the eyespot leaves the 20° x 20° view forward. Thus the rate the driver is mirror- or instrument-sampling can be ascertained as can head movements, blink rates, time (in 10 ms intervals from a digital clock) and pupil size.

Although eye-movement techniques offer a new area of investigation of the driving task, it is an expensive process to analyze the data. Data analysis requires a frame by frame analysis of the time and spatial position of the foveal fixations. X-Y plots would be useful only if the visual field were fixed, but unfortunately in driving the field is constantly changing before the driver. Basic analysis formats involve temporal analysis using fixation histograms, or fixation aggregation histograms. In the latter case we may elect to sum all fixations

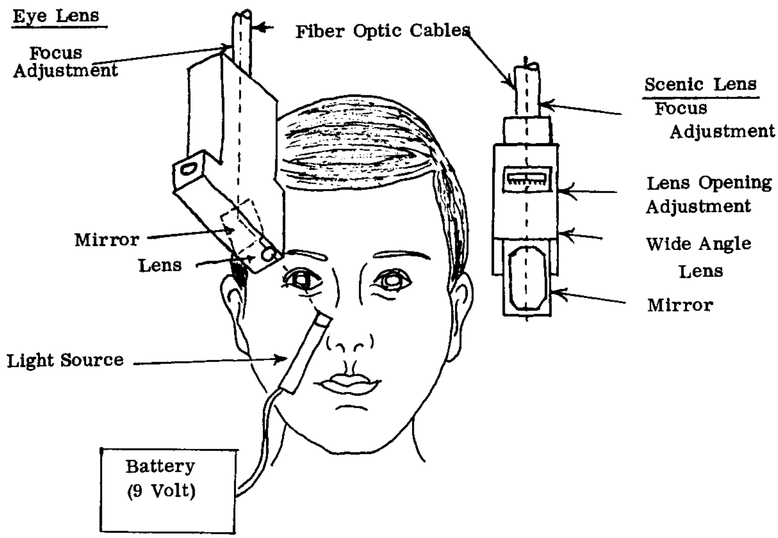

FIGURE 1. *Input System*

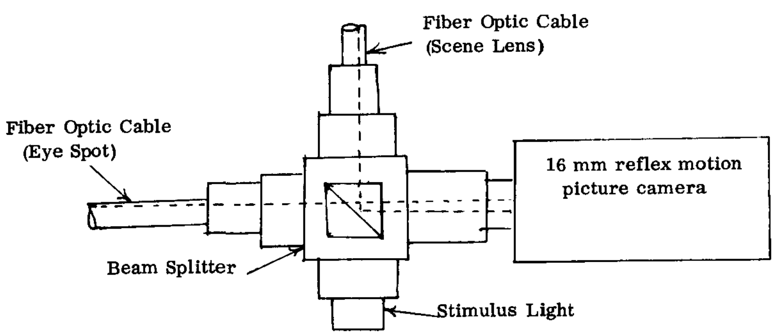

FIGURE 2. *Output System*

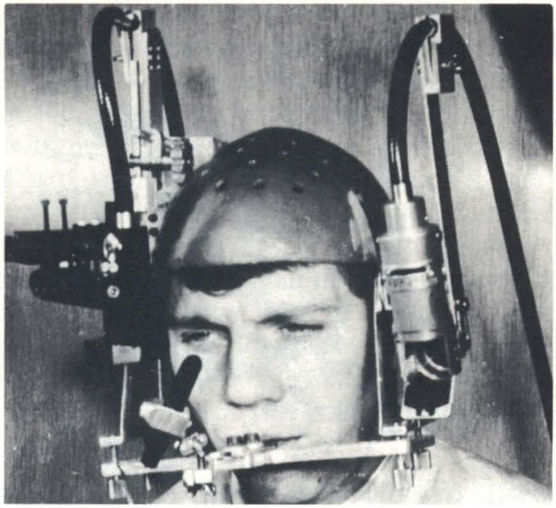

FIGURE 3a. *Subject Wearing Head-Piece and Input System*

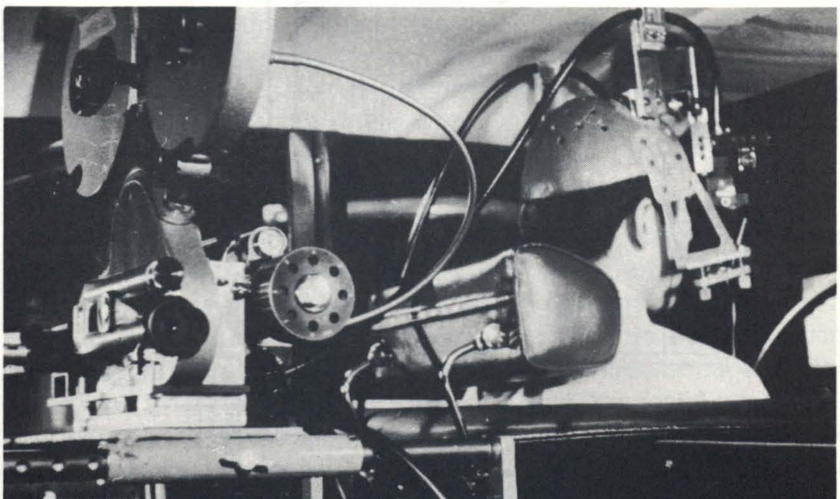

FIGURE 3b. *Subject and Apparatus in the Experimental Vehicle*

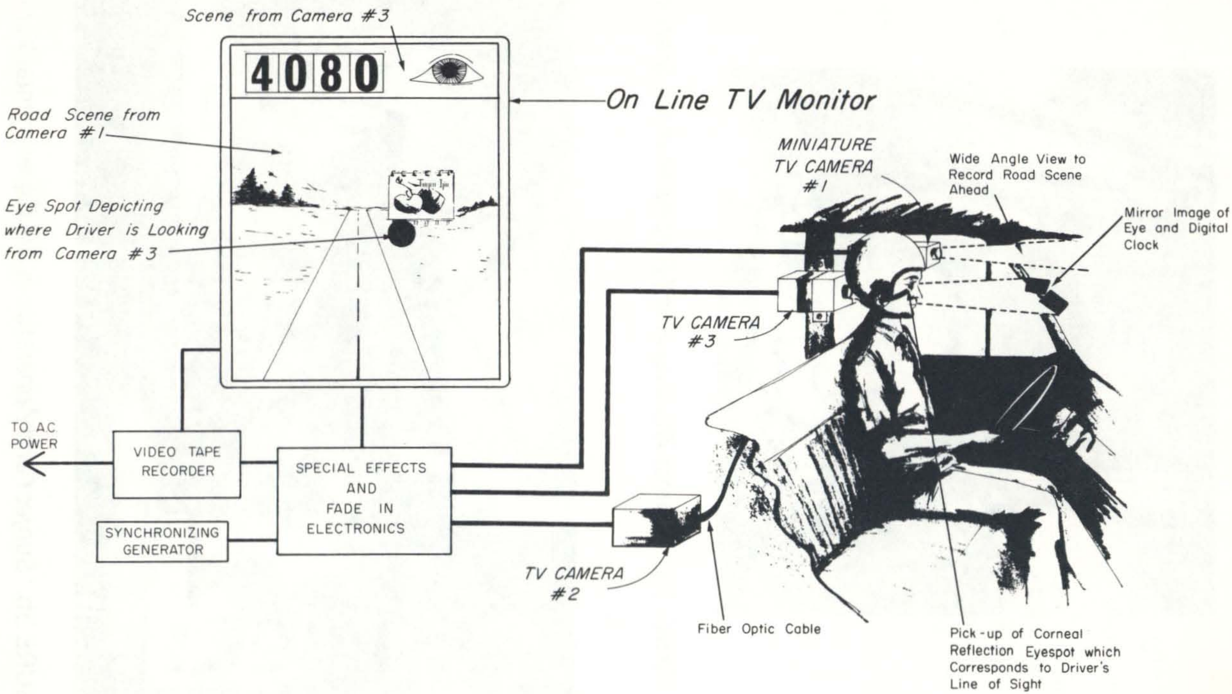

FIGURE 4. *Television Eye-Movement System for Automobile Driving*

within a two degree area and call this phenomenon a gaze, or a look. Eye movements may also be analyzed by spatial density maps given that one understands what a coordinate means in terms of the driving task and environment. Eye movements can be analyzed as a Markovian process examining transition probabilities, i.e., the probability of the eye moving from one spatial segment to another or from one object to another. A particular segment of eye-movement data can be analyzed by recording the distribution of eye travel distances. Object analysis is becoming a more and more common procedure whereby one describes the percentage of time that the driver spends on cues in the scene, such as signs, delineators, the car ahead, etc. Spatial-temporal analysis, that is, the percent of time the eye spends in a given location, is still probably the basic approach in analysis. In addition, eye movement can be identified by the degree and amount of pursuit eye movement in terms of the total visual task.

Finally, a clarity concept based on visual discrimination capabilities has been used extensively in recent research on signs to investigate availability of information contained in retinal images of signs. For general applications, clarity is defined as the angle subtended by four-inch critical detail divided by the resolution angle at the eccentricity angle (where the image of the detail in question falls at some eccentricity angle from the fovea). This is called an index of clarity and is operationally useful in determining what information in the scene was available to the driver with a given fixation.

Research Potential in Eye-Movement Technique

In describing eye-movement research, it is important to point out that eye-movement research probably has fewer artifacts than any other technique used to measure driving performance, because there are no instructions on how the driver is expected to use his vision. Unlike response time studies, vehicle control studies, or car-following studies, the driver has no indication as to what constitutes "good" performance. Thus the task is essentially instruction free. If one decides to study signs, one never tells the driver that he is interested in sign fixation. It must be admitted, however, that the wearing of this equipment may well influence eye-movement patterns and head movement, although recent data has indicated little differences in head movements with and without the head-mounted eye-movement device. The fact that drivers can wear the helmet for two and three hours and the fact that drivers in fatigue research will actually fall asleep with the device in place would suggest that subjects can adapt reasonably well to the system.

Before discussing the results of various studies in eye movements it might be useful to point out some of the attendant interpretation problems. The field of view is restricted in eye-movement research. The system using 16 mm camera has a 20° x 20° field. The newer system is closer to 50° x 40° and permits identification of mirror and instrument sampling when eye fixations leave the scene ahead.

Because eye movement research is embryonic, a few major limitations in interpretation must be faced. First, in most cases the driver has considerable spare visual capacity. Most interstate driving probably requires less than 50 percent of a driver's perceptual capability. Thus, we frequently find the driver deliberately sampling completely irrelevant information, such as covered signs, at repeated intervals. The second major problem in eye-movement research is the role of peripheral, or extra-foveal vision. A fixation may be merely a reference point for organization of peripherally acquired information. Our research indicates that extra-foveal vision plays a large part in driving. Indeed, it may well be said that driving is largely a dynamic peripheral vision task. Foveal vision is important in terms of its characterstics of finer discrimination (e.g., sign reading) and higher rates of information extraction, such as quick glimpses at on-coming vehicles on undivided highways. It is no surprise that research has found little correlation between visual foveal acuity and accidents, because visual acuity may be less important in driving than the detection of movement by peripheral visual processes. A third problem in interpretation is that the driver may be looking at an object but he may or may not be processing the information.

Despite these drawbacks, however, we feel that there are some interesting and provocative results derived from eye-movement research to date. Eye-movement studies have proved to be useful as a means of measuring degradation of driving performance as a result of intra-subject factors, such as experience, alcohol, fatigue, and environmental factors, e.g., illumination, traffic load, etc. It may also be useful as a predictor of control movements. However, the automobile is a highly damped, forgiving system that permits a wide variety of both eye movements and control movements to achieve essentially the same vehicular dynamics. Eye movements are often related to gas pedal deflections, and both may be useful in describing uncertainty in driving. Finally, application to highway signing and highway design shows considerable promise.

The visual task in driving may be described as the monitoring of the continuous stream of information present in the environment through which the vehicles travel. At a given instance the foveal region of the eye examines only about a 2° circular (diam.) region of the stream. Much more of the information is available to the extra-foveal portions of the eye. There is some evidence (Mackworth, 1965 and Sanders, 1966) that the planning of eye movements is partially controlled by information received through the periphery of the eye. For example, a vehicle traveling in an adjacent lane may first be detected peripherally and confirmed foveally. Because the visual function of information seeking plays a basic role in the driving task (Connolly, 1968), several benefits may be realized from describing the search and scan behavior of drivers. For example, Walraven and Lazet (1966) have suggested that a record of drivers' eye movements may provide a better method of assessing driving skill than has been available in the past. This assumes that analysis of eye-movement patterns of experienced and accident-free drivers will result in the development of criteria for good search and scan patterns. If such criteria were developed, they could be used to assess drivers' visual performance by objective quantitative measurement during licensing examinations. Eye-movement research may also improve the content of driver education programs. Standard methods may be developed to teach inexperienced drivers good search and scan patterns. Finally, the relationships between perceptual load and driving environment may be explored by studying driver eye movements. The effects of various types of highway geometry, traffic conditions, road signs, visual aids, and vehicle designs could be evaluated by recording and analyzing driver eye movements.

Studies Toward A Theory of Eye Movements

At Ohio State University eye movements have been used in a variety of experimental situations. Experiments have been conducted to measure the effects on search and scan patterns during performance degradation situations. Another set has been concerned with evaluating the highway environment, e.g., signs, curves, etc. A third set has been directed at developing a theoretical explanatory model of eye search and scan patterns.

Considering the latter objective, drivers were studied on unopened stretches of interstate highway to find if replication of eye movements could be demonstrated. Using spatial and temporal analysis, it was found that drivers in open road driving at 65 mph on the same test section give essentially the same pattern of eye movements. Changing the test section landscape background introduced statistically significant changes in spatial density plots, even though the road geometry and the task remained the same.

Next a series of tests was designed to permit the driver voluntary occlusion. He was encouraged not to open his eyes while driving on a straight highway section. Mean occlusion time was found to be inversely proportional to velocity. In addition, initial fixations (orientation fixations of 100 msc on the average), which tended to be short, were then followed by fixations on lane markers or on points from which reference to lane markers could be ascertained. At 40 mph the occlusion interval averaged three seconds followed by fixations approximately 3½ to 4½ seconds ahead of the vehicle. With experience, drivers tended to minimize orientation fixations and lengthen occlusion intervals. Further, viewing time appears to be a function of the regions in the visual field on which the driver fixates rather than just the velocity.

Other studies confirmed that as passengers, individuals had significantly different eye-movement patterns than when they were acting as drivers. The search pattern was wider, more dispersed and less reference-oriented (e.g., at lane markers or shoulders) than when these same individuals performed as drivers. Instructions for increasing lateral control accuracy led to increased concentration of fixations near the focus of expansion.

Because of the suspected role of peripheral, or extra-foveal vision, in driving, a series of studies was conducted in which the driver, while car following at 100 feet and 70 mph, was asked to concentrate his sampling on a target car at some eccentricity angle to a line of motion of his vehicle. Detecting Landolt rings in the rear of the target car served to test the driver's skill at this task. It should be noted that whether the driver complies with the instruction is readily apparent from the eye-movement records. As the eccentricity angle increased the driver stole more fixations at or near the lead car. In general, however, for angles up to 20 degrees the driver would essentially maintain placement and headway in his own lane with few if any fixations on the lead car. Any perturbation in the velocity pattern introduced by the lead car, however, led to more foveal fixations or fixations close to the lead car. Increasing lane position accuracy gave the same effect. In general, the driver can get enough peripheral cues to maintain adequate lateral and longitudinal placement in his own lane despite large eccentricity angles. It is hypothesized then that in normal freeway driving the driver uses extra-foval vision to maintain lateral placement while directional cues are simultaneously determined foveally.

This hypothesis is somewhat confirmed by the tendency of novice drivers to sample close to the vehicle. Eye movements in close to the vehicle are still used to pattern a curve or verify placement, while the farther fixations sort out on-coming traffic and future curve directions to dictate later samples. Gordon (1966) supports the role of peripheral vision as the detection process for later foveal confirmation. In his experiments, monocular vision was provided for the driver with a very small aperture which forced him to use foveal fixations to pick up data that are normally available to him peripherally.

Although a theory of driving search and scan patterns has not been developed to date, early study of the process suggests that it is indeed a complex mechanism and one in which peripheral, or extra-foveal vision, plays a major role. In addition, if the driver is not loaded perceptually, a considerable amount of external noise is introduced into the data because of what we might call eyeball exercises, or random eye movements, which apparently have little relevance to the driving task. This is particularly evident in scenery patternings in low traffic density situations.

Studies of Eye Movements in Driving Degradation Conditions

While intersubject differences in driving eye movements are difficult to analyze because of the varied idiosyncratic perceptual characteristics of drivers, it is possible to use eye movement techniques to study intrasubject differences as a function of degradation situations such as alcohol, carbon monoxide, and fatigue. Here eye movement changes can serve as early detectors of subsequent control process degradation.

Belt (1969) examined eye movement changes as drivers were studied at blood alcohol levels of 0.0, 0.04, and 0.08 mg alcohol per cubic centimeter of blood. In these cases, eye movement patterns were dramatically affected. At the 0.04 level, some concentration of eye movement pattern was apparent. At 0.8, significant perceptual narrowing, or tunnel vision, was evident. In this case, using a concentration index (defined as the percent of time the fixation occurs in a 3° x 3° space near the focus of expansion), it was found that in open road driving the concentration index went from 25 percent in the control case to 40 percent at the 0.08 blood alcohol level. In car following, one driver elicited almost a complete lack of search outside of the concentration zone. Passing vehicles were always fixated when the driver was sober. However, at 0.08 level the driver made no fixations on cars passing, suggesting the degradation of peripheral detection. Fixation duration tended to increase with increasing alcohol level. Finally, since lateral control was lost twice in these studies at the 0.08 level, it was decided to investigate what eye movement patterns preceded these conditions. It was found that prior to loss of control, the driver reverted to his sober sampling techniques. The implication from this study suggests that perceptual narrowing is an adaptive process that the driver needs in order to maintain any semblance of control. Abandoning this compensatory action leads to loss of necessary control cues. It is believed that eye movements will reflect the effects of alcohol long before overt control or measured driving performance degradation is detected.

Kaluger and Smith (1970) employed eye movement techniques to study the performance of drivers with and without sleep in the previous twenty-four hours. In the fatigued state, drivers were observed with a large number of fixations in close and to the right of the highway, which the authors interpreted as a foveal compensation to offset diminished peripheral detection capability. In addition, they observed that while no pursuit eye movements were found in the control conditions, subjects exhibited pursuit eye movements almost 5 percent of the time in the sleep loss condition. Despite the use of the testing equipment, the fatigued driver would frequently doze or close his eyes for one to three seconds during the test runs.

Learning and Search and Scan Patterns

Considerable efforts over the past few years have been directed to visual information seeking of novice drivers. Zell (1969) and Mourant and Rockwell (1970) have discovered significant changes in eye movement patterns with experience. Most of the differences are reflected in spatial rather than temporal changes. Figure 5 shows the typical novice driver's shift of horizontal fixation patterns with training. Figure 6 shows that during their training, drivers switch from frantic cue searching, large eye movement travel distances and fixations on nonrelevant cues such as lamp poles, guard rails, etc., to alternate sampling near and far. The far fixations are thought to be primarily directional cues while the very near samples (usually less than one second ahead of the vehicle) suggest foveal determination of lane position. The experienced drivers concentrate fixation near the focus of expansion and are thought to use peripheral or extra foveal processes for lane positional feedback.

In the main, students early in their driving experience fail to adjust their preview sampling as a function of their velocity. Experienced drivers, on the other hand, attempt to maintain a good 2½ to 3½ seconds minimum preview time, adjusting their forward reference distance with velocity changes. Novice drivers, especially in their early hours of driving, sample close in to the car. This may be due to their inability to make temporal-spatial estimations.

Eye Movements and Sign Reading

Considerable effort has been made over the past two years to evaluate signs by using eye-movement techniques. The Cleveland Memorial Shoreway has been studied before and after sign upgrading to DOT specifications. A computer program has been developed which

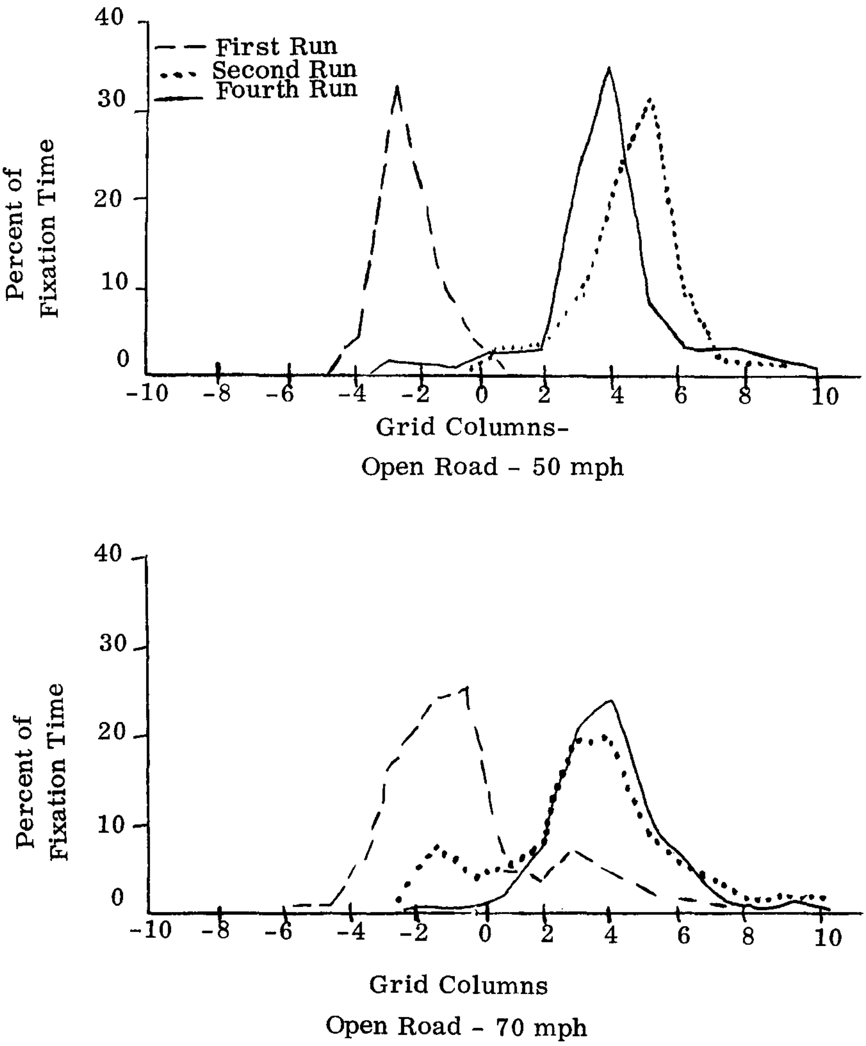

FIGURE 5. *Percent of Fixation Time for Grid Columns as a Function of Vehicle Velocity and Driving Experience*

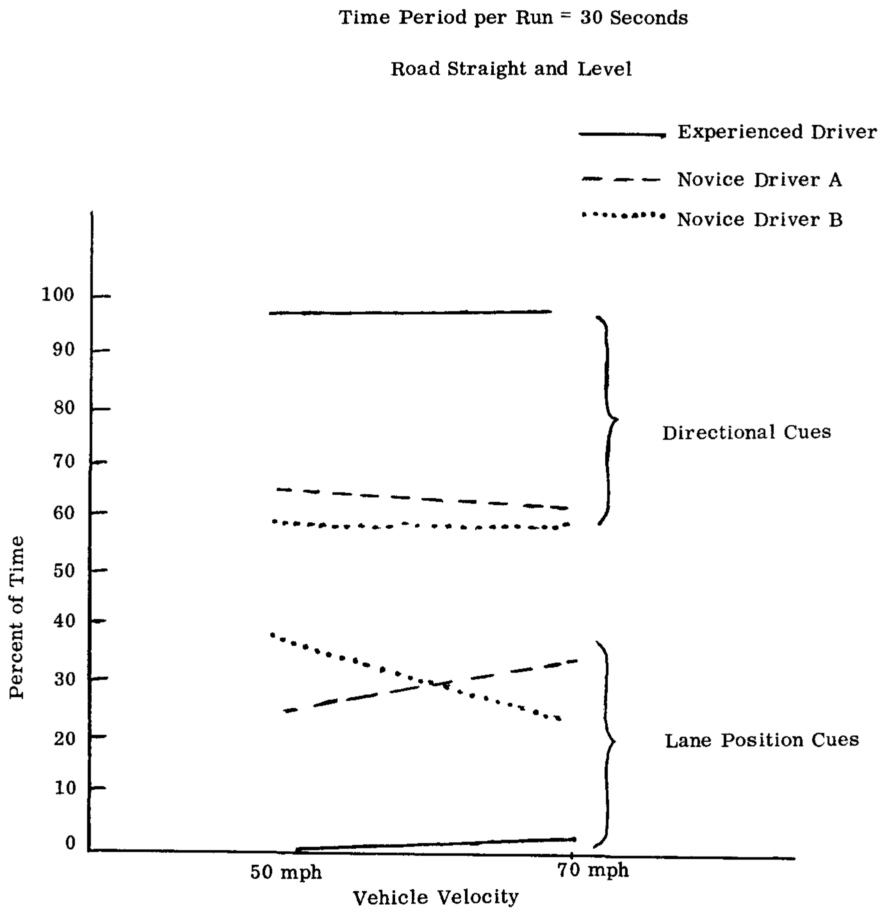

FIGURE 6. *Percent of Time Sampling for Directional and Lane Position Cues as a Function of Vehicle Velocity*

combines eye-movement patterns, speed of the vehicle, lane position, visual acuity of the driver, sign design features, and roadway geometry. Out of this we can ascertain the earliest possible time for sign message resolution with a given accentricity angle (angle relating the eye fixation point to the sign position), the earliest and latest time the driver samples, and the degree of time-sharing between the traffic, road, and sign, within this interval. It was found that high perceptual loading (for example, as in car following), sign quality can be differentiated by eye-movement techniques in terms of the time necessary to receive the information from the sign relative to the time which the sign information is available and acknowledged so by the driver's sampling program.

Summing Up

The potential of eye-movement techniques in understanding driving phenomena is virtually untapped. Eye-movement research has developed sufficiently over the past four or five years to begin the study of other facets in the driving task. These include the possible effects of carbon monoxide, narcotics, and marijuana on information acquisition, the effect of background and landscaping on curvature search patterning, the effects of driver aided systems (e.g., heads-up displays), and the effects of glare, rain, and fog on search patterns. While eye-movement research focuses on only one aspect of the total driving task, it is significant that without knowledge of the information acquisition side of driving, no real development in driving theory such as information processing, anticipation, and learning can be developed. Any generalized predictive model of driving will have to have quantification of the informational inputs to the driver.

Today's vehicles, highways, traffic control devices, driver education programs, licensing tests and laws are all based upon our knowledge of the driver. Until recently, we were ignorant about the nature of that subsystem of man which is the basis for most driving behavior, namely, the visual information system. Now at last we are beginning to get some insight into this perceptual system and how it can be used to improve our knowledge of the driver and lead to safer design of highways and vehicles.

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DISCUSSION

Stephen R. Schroeder

Dr. Schroeder is Clinical Assistant Professor in the Department of Psychology of the University of North Carolina at Chapel Hill. He holds a Ph.D. in experimental-physiological psychology from the University of Pittsburgh. His published research reflects a wide range of interests, but one major area concerns the study of eye movements under carefully controlled laboratory conditions. Dr. Schroeder is currently engaged in research relating eye movements to the driving task.

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A Perspective for Research on Driver Eye Movements

The field-testing unit developed by Dr. Rockwell and his colleagues is a good example, I think, of an elegant technological solution to a problem posed by theory. In view of the development of advanced technology for the investigation of the role of oculomotor control in highway safety, it might be useful to reflect briefly on the status of relevant laboratory research on oculomotor systems and its implications for future technology. What contributions can this research make to the solution of the problems of highway safety?

To do this, I would like to review some areas of research on oculomotor systems which relate to the functions of eye movements in driving and suggest some useful ways of thinking about this problem. Two general areas of psychological research are especially pertinent: research on the oculomotor system as an information processing device and research on the functional characteristics of eye movements.

Systems Characteristics of Oculomotor Control

From a systems point of view the driver may be considered the critical component in a negative-feedback, man-machine system. He is the main processor of information and the critical element in making decisions to alter or maintan the system in a given state. Data about the driving task are fed to him through various servo-systems, of which the oculomotor system is a principle component.

The sequence of events for such a system might be the following:

(1) The driver searches a scene of selectivity patterned stimuli. Pattern selectivity is already determined before fixations occur by the physical characteristics of the stimuli themselves, the driver's familiarity with the scene, and his history of reinforcement for viewing it.

(2) The driver concentrates fixations on selected items, fixating each successively during which time he abstracts and encodes the critical features of each stimulus.

(3) The encoded features are compared with some memory device.

(4) This information is converted to action—or inactions—on driver behavior.

(5) Change in fixation location occurs and the cycle begins anew.

The question might be asked, "How do the physical capabilities of the oculomotor systems fit the negative feedback model?" The answer seems to be, "Very well." From an evolutionary point of view there seems to be a high degree of correlation between the development of foveal vision and the development of extraocular muscles (Westheimer, 1969). Apparently the purpose of extraocular muscular control is to keep a region of object space fixed on the retina. Accordingly, extraocular muscles react to impulses of nuclei in the central nervous system much faster than other muscle systems of the body, e.g., an arm or leg. Furthermore, the movements of both eyes, except for vergence movements and micronystagmic movements, are always coordinated and parallel in higher mammals. While the eyes can be held steady within a few minutes of arc, the largest excursion from midline is between 20-30 degrees visual angle in each direction at velocities as high as 600 degrees per second for larger excursions. The net effect of this arrangement is that the eye usually spends about 90 percent of its time fixating and about 10 percent of its time in discursive movements.

The oculomotor system, during search, operates in either of two modes: with smooth movement, when tracking targets with velocities of up to 30 degrees (visual angle) per second or less; with saccadic movement, when searching for visual targets. Saccadic movements are fast, binocularly identical movements which cannot be interrupted once initiated. They occur as jumps from one stimulus to the next or as resetting movements during pursuit of fast-moving targets.

It can be seen that the saccadic eye movement response pattern fits nicely with gating of information required by the negative feedback cycle proposed earlier. The question may arise, however, "Is fixating during driving a perfectly nominal gating system?" Can eye fixation parameters be related to information uptake bit-by-bit? If such were the case, one might visualize the eventual development of a mathematical Markov process, as Rockwell mentions, where it should be possible to predict where the driver would look next as function of what he was fixating just before.

The benefits of such an exercise for analysis of driver performance are obvious. Unfortunately, attempts at such analyses even with static displays have not been very successful thus far. Gould (1969) noted that conditional probability analyses for pattern recognition tasks were not very useful. Senders (1966) was only moderately successful in predicting transitional sequences of fixations of pilots in an airplane cockpit. The difficulties encountered in mathematical models of attention for simple multiple-cue learning tasks (see Trabasso and Bower, 1968) suggest that it will be some time before such analyses have practical utility.

This is not to deny that patterns of fixation sequencies are important. The recent work of Noton and Stark (1971) relating "scanpaths" to memory traces of pictures is an excellent example of evidence that they are.

The complexity of the driving task, however, probably imposes a limitation on the applicability of the information processing model to eye movements and driving behavior. With driving behavior, an additional complication involves the fact that the scene changes continuously and the constancy of change is under the control of the driver. Thus fixed location of the eye with reference to the head might actually be a tracking movement with respect to position of the vehicle, e.g., during car-following. The data of Rockwell, however, would seem to suggest that such tracking eye movements constitute a small proportion of fixation time during driving relative to the large numbers of saccadic eye movements. The pursuit movements of fatigued drivers found by Kaluger and Smith (1970) should be distinguished from those of alert drivers. Slow pursuit movements found in subjects when monitoring static displays for long periods of time (Schroeder, 1968) are usually correlated with fixating without detecting. They are thus probably more like the slow pendular eye movements found in the early stages of electrophysiologically defined sleep, representing a decline in arousal (Weitzman and Kremen, 1965) and not a differential sensitivity to external stimulation.

Another question related to the systems model for driving is the notion of channel capacity. According to this notion selective location of fixations is correlated with higher order processing of information by the nervous system (Noton, 1969). Selective fixation patterns would then reflect attention to salient features of the driving scene. The question of interest is whether the driver can attend to several features of the driving scene simultaneously or whether he must attend to each in succession.

These questions have been attacked for static stimulus displays by the use of tachistiscopically presented material. Information is presented to the subject in brief flashes and he is then asked to recount or identify what he saw. Results of these studies (Neisser, 1967; Sternberg, 1967) indicate that the amount of information processed simultaneously depends greately on practice and the error rate which is tolerable.

This problem may be important for driver performance where error rates in driving are hopefully low and sudden stimuli may occur, as in accident-producing situations. Studies with static displays indicate that visual noise (increased irrelevant stimuli) causes tunnel vision (Mackworth, 1965), that is, the subject focuses fixations to fewer stimuli within a smaller area. The real possibility exists that tunnel vision, i.e., reduced scanning fixations, develops under stressful driving conditions, e.g., icy roads, congested traffic (Mourant and Rockwell, 1970). Such selective fixation would reduce the driver's capacity to detect sudden danger stimuli or more peripheral stimuli and therefore would be undesirable. Driver training under stressful driving conditions might be very valuable for accident prevention.

A third area of investigation where the negative feedback model has proven useful has been in the analysis of time relations between sensory input and sensory-motor feedback and their importance for driver performance. Young and Stark (1963) have shown that predictability of moving targets is important for visual tracking accuracy. Smith and his associates (1970) have shown that eye-hand coordinated movements must be in synchrony for accurate tracking and steering behavior. If feedback from steering movements to the oculomotor system is delayed by as little as .1 sec., the accuracy of subsequent steering adjustments decreases sharply. His results suggest that a major factor in safe driving is not only reduced speed but the elimination of instrumentally produced steering delays, such as frequently occur in automobiles with power steering.

Functional Characteristics of Oculomotor Movement

The areas just described are but a few areas where the negative feedback conceptualization has been useful for generating experiments and interpreting results relevant to driver performance. There is another way of thinking about oculomotor responses that has also been very useful. This approach concentrates more on the functional characteristics of eye movements. Researchers using this approach are more concerned with what eye movements do in particular situations rather than how the whole system fits together. It is not possible to review all the relevant literature here. Suffice it to say that eye movement parameters are highly sensitive to the way spatial and temporal information is presented.

Laboratory research on eye movements indicates that saccades serve three main functions (Schroeder, 1970):

(1) During search and familiarization, fixations serve a sampling function. A stimulus, foveal or peripheral, may serve as a signal for saccade, so that subsequent foveal fixation can extract information more efficiently.

(2) Selection, i.e., suppression of irrelevant information, may occur when information is gathered through peripheral vision and the foveally centrating saccade is either unnecessary or incompatible with efficient information gathering. Thus concentration of fixations in one area changes the useful field of view, making more peripheral stimuli less detectable.

(3) The peripheral stimulus may be a signal for refixation and thus provide a verification or rehearsal function.

The principle mechanisms of function are: (1) stimulus control exerted by stimulus parameters, e.g., intensity, duration, novelty, affective tone, context; (2) feedback relations, i.e., the contingencies for reinforcement; and (3) familiarity, e.g., practice and instructional set.

The fact that these functions are born out in a wide variety of experimental situations with static displays, e.g., pattern recognition (Gould, 1967), problem solving (Kaplan and Schoenfeld, 1966), inspection of aerial photographs (Mackworth and Morandi, 1967), signal detection (Schroeder and Holland, 1969), and discrimination transfer (Schroeder, 1969), enhances the likelihood that eye movements subserve similar functions during driving. Indeed the data discussed by Dr. Rockwell suggest that this is the case.

A considerable number of studies are now available that show that drivers display selective distributions of fixation location, e.g., Thomas, 1968; Whalen, Rockwell, and Mourant, 1968; Mourant and Rockwell, 1970. There is some evidence that task variables such as speed and traffic conditions (Whalen, Rockwell, and Mourant, 1968) affect the location of fixations. Familiarity also has some effect both as a function of driver training (Zell, 1969) and instructional set about route information (Mourant and Rockwell, 1970). Alcohol (Belt, 1969) also seems to have an effect on fixation distribution and duration. It is also noteworthy that rate of shifting of fixation and fixation durations for most of these studies fall within the ranges commonly noted in the laboratory for the scanning of static displays.

These studies have been largely exploratory, but they have laid the groundwork for a more thorough functional analysis of eye movements and driver performance. It now seems possible that eye movement research will become relevant to the training of safer drivers and to the creation of more optimal conditions for driving. But before these goals can be approached a great deal of eye movement research will have to be done to establish functional relationships between what the driver sees and what he does with his automobile as a function of his oculomotor responses. Eventually, it will be necessary to know *more* than that a driver spends a certain percentage of time fixating roadmarkers when driving at a certain speed. To be useful such information will have to be a part of a relationship between a more specific driving situation and the consequences of the driver's performance.

In this regard, a rational approach might be to examine specific driving subroutines, such as car-following or car-passing, and attempt to relate fixation patterns to optimum performance with the vehicle in that situation. Much of the research of this type will of necessity be laboratory research where stimulus and response parameters can be precisely specified. The stimuli reaching the driver's visual system will have to be controlled and abstracted for critical features. Many situations are permissible in the laboratory which could not be permitted in a real road-test driving situation, e.g., training drivers to avoid accidents in dangerous situations.

In closing I would like to reemphasize the necessity for coordinated laboratory and field study in future eye-movement research. Both are necessary and can be mutually beneficial when they feed questions and answers back and forth. The technology which is "mushrooming" in the field of traffic safety is gratifying, but our technology should mirror closely the problems we want to solve. In many cases, laboratory research can be helpful for sharpening and answering the questions pertinent to driver performance on the road. On the other hand, the complexity of the driving task and relevant field study pose a challenge for laboratory researchers to make their theory relevant. Thus the road test will be the final proving ground for theory, but a balance between theory and technology must be maintained.

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Section III

Research in Automotive Human Engineering

John Versace

Discussant

Stanley M. Soliday

JOHN VERSACE

Beginning his studies in electrical engineering and physics, Dr. Versace eventually changed to engineering psychology and completed his Ph.D. in 1955 at Ohio State University. In 1956 he joined Chrysler Corporation as a human factors specialist, consulting with designers. There he became deeply involved in the psychophysics of the vehicle ride. In 1962 he joined Ford Motor Company, where he worked with a small human factors research group. He is now responsible for research in the broader area of vehicle safety, driver vision, occupant anthropometrics, vehicle controls and handling, occupant protection and human tolerance to impact, structural dynamics and physical crashworthiness, and accident statistics. He also provides information and guidance to those who are responsible for product development and corporate policy.

His work includes both laboratory and on-the-road experimentation, as well as computer simulation and model building.

RESEARCH IN AUTOMOTIVE HUMAN ENGINEERING

By John Versace

It is easier to define performance requirements for devices or designs intended to be injury-reducing, and to predict their effectiveness, than it is to define or to predict the effectiveness of actions or countermeasures intended to reduce accident occurrence. Injury-reduction deals mainly with physical parameters; accident-avoidance mainly with behavioral parameters.

The train of "antecedent contingencies" germaine to injury reduction, begins at the instant of collision and terminates at the point of injury. These antecedent contingencies are physically specifiable, at least in principle, and they determine the physical consequences. And they are usually describable in terms of a simple time series of events.

On the other hand, much of *accident-avoidance* deals with a set of antecedent contingencies which precede the collision, and they are not likely to be arrayed in a simple series of one-after-the-other events. Furhtermore, they cannot be conveniently expressed in terms of basic physical units, but rather involve conceptually vague and only indirectly measurable entities: driver perception, expectation, awareness, alertness, judgment, intelligence, adaptability, knowledge, motivation, attitude, aggressiveness, etc. It is very difficult if not impossible to estimate accident reduction effectiveness on the basis of presumptions about these antecedent contingent entities, or even to make a confident postulation of the likely train of contingencies prior to an accident. And therefore, designing the vehicle to make it "easier to drive" (whatever that may mean in operational terms) does not have any logically necessary relation to increased safety performance—in the sense of being determined through operation of simple physical laws.

Driver Adaptation

In the case of injury occurrence, there is little that a driver can do—once the train of collision contingencies is touched off—to quickly modify his physical condition so as to significantly affect the consequences of a blow to his body. The injury-occurrence sequence tends to be "open-loop," or "ballistic," in that the train of events proceeds systematically to their conclusion: physical trauma to the occupant.

But the accident avoidance situation is "closed-loop," or self-regulating. The collision itself is not a strictly predetermined event because the driver has a large repertory of behaviors available for accommodating to the behavioral contingencies as they arise. Thus, he can move his head to increase the field of view in his rear-view mirror. If he cannot see very well while driving at night, he can reduce his speed to the point that the illumination is adequate for his performance. If he cannot reach a control while sitting erect, he can bend forward. If he is getting tired, he can stop driving. If driving on a wet surface tends to make his car unusually sensitive, he can lower his speed or otherwise subdue his steering actions. If another car is recklessly merging into his lane, he can slow down or steer away to avoid it; or he may do both, and he can do them in infinitely different degrees of combination.

In other words, he can change the contingencies that precede a potential accident. He can bring into existence new ones as a result of his adaptive behavior. These events are diffcult to describe and impossible to exhaustively list. And they cannot be specified in physical terms that are commensurate with those a designer can use (for example, how would you relate some non-metric description of driver expectation of how unobstructed the dark road ahead of him is, to headlamp candlepower?). This means that we must often deal with conceptualizations expressed in terms of the risk, or probability, of events and consequences, rather than those based upon the usual physical units of measurement. Although we can name the particular conditional probabilities that will be involved, we cannot readily make any logical or experimental prediction of the degree of performance adequacy without actually going out and observing the occurrence and non-occurrence of accidents, given the various design features under consideration.

The adaptive or self-regulating character of drivers may sometimes be self-defeating. Steps taken to improve behavior may actually reduce performance capability. For example, increasing headlight illumination increases the visibility distance. This allows the driver to go faster, which may increase hazard. Alternatively, there is a powerful urge in most drivers to dip headlights in deference to an oncoming motorist. Increasing the candlepower will generally result in increasing the glare, and thus cause many drivers to dip the lights sooner. This can result in longer intervals in which the driver uses low-beams instead of distance penetrating high-beams.

Safety Validity

What is the validity of human factors measures? That is, in the usual psychometric sense, what do the dependent variables and the fixed and experimental conditions of the study have to do with the ultimate criterion: the relative degree of lethality, the frequency and extent of injuries and deaths? In psychological testing, there is explicit concern over correlation with the ultimate criterion. In the safety field, difficulty of getting at the ultimate criterion often leads to presumptively treating intervening variables as if they were the final criterion. Critics can ". . . correctly point out the practical temptation to measure the easily measurable and to use the measurable as the sole criterion, even when it is only marginally relevant. They correctly point to the way in which what can be measured distorts a program and becomes the program goal" (Donald T. Campbell, Northwestern University).

Another quotation, from A. Chapanis of Johns Hospkins, on this issue:

> On what basis does an experimenter select a dependent variable to use in his experiment? Even at the risk of alienating some good friends, let us be honest: Dependent variables in laboratory experimentation are most frequently selected for their convenience to the experimenter, rather than for their relevance to some practical problem. I mean by this that the choice of a dependent variable in laboratory experimentation is often made on the basis of what is most likely to yield a significant result, and so a publishable paper. Indeed, I have seen experimenters try one dependent variable after another until they finally hit on one that would give them the result they wanted. Entirely aside from the interesting logical question of what constitutes a statistically significant result under these circumstances, there is the more important consideration that dependent variables selected in this way may have very little to do with what we need to know to solve problems.

> Now look at this matter the other way round and ask what kinds of criteria real-world problems demand. What criteria does the systems engineer use, and in what terms does he need to have data presented to him?

The effect of driver adaptation, or compensation, is to reduce the correlation of the string of intermediate variables that lie between the most proximal ones of vehicle design, and the ultimate criterion, accident avoidance performance. For example, the design of a signal should influence the driver's ability to see it, which should in turn influence his ability to react to a critical situation, which in turn should affect the accident outcome. Viewing each of these intermediate processes as overlapping sets, with the degree of overlap reflecting the correlation between adjacent ones, it is easy to visualize that those sets at opposite extremes of the string may have only small overlap with each other. For example, if there is only *one* intervening variable, and adjacent variables correlate as much as 0.9, the correlation between the first and the third can range between .62 and 1.0. Of course, for smaller and more likely values of these correlation coefficients, the 1st-to-3rd relationship will be even more tenuous. There is no assurance that merely because X is related to Y and Y is related to Z, that X will also be related to Z!

Specific Areas of Human Factors Research

Human factors considerations in the design of the vehicle occur in four main categories:

- *Vision,* which relates to signals, illumination, and impediments to viewing.
- *Controls,* both in proximal aspect and with respect to vehicle maneuverability.
- *Anthropometrics,* or fitting the vehicle to the geometry of the operator.
- *Biomechanics,* the determination of human tolerance to crash impact.

VISION: Signal Lights

Numerous experiments and controlled observations have been made over the years by automotive engineers and by lighting and human factors researchers. Juries are commonly used to evaluate the adequacy of the signals, often under extreme ambient conditions, such as in very bright Arizona sunlight. These evaluations are the basis for establishing the performance requirements that are then incorporated into standards of the Society of Automotive Engineers. These engineering standards have thus far also been a significant basis for Federal Motor Vehicle Safety Standards.

The jury evaluation method is very valuable, but we also do experiments with more quantitative measures. For example, vehicles with experimental signals are followed at various distances and the reaction time of the following drivers is measured. Numerous experiments have been done to evaluate the color of signal lights. Although most observers can detect taillights a mile or more away, they cannot always recognize the color, especially if it is not red. We have also done signal light studies in fog, through courtesy of the University of California, and find that perhaps twice as much intensity of green light is needed for equivalent detectability, as compared to red.

Laboratory simulation is also used, and the performance of the experimental subjects has been expressed in terms of the confusion matrix, and by a detection theory paradigm, in addition to reaction time measures.

Our studies have led us to believe that a ratio of 10 times between the intensity of the brake signal and the taillight will provide both minimum reaction time and positive identification. Another result of our work has been to make available supplementary signal lights mounted in a high location, starting with certain of our 1969 cars. These signals can be seen through intervening vehicles, thereby giving advance warning of changes in traffic. And they present a very distinctive signal pattern when actuated.

The Problems in Interpreting Laboratory Tests

Our experiences in signals research points up some of the problems previously discussed. There are at least three problems: first is the choice of a response measure which has something to do with safety, as was discussed previously. Observer reaction time is often used, but psychologists are likely to regard reaction time—or visual acuity—as a naive measure. The second problem is there is no way to calibrate the degree of stress imposed in a laboratory experiment to make it operationally equivalent to the degree of stress occurring in real-life driving. As a result, stress in the laboratory is often increased until success in the experiment is obtained; that is, to the point of statistically significant differences in the experimental conditions. And that is the third problem: the degree of statistical significance alone is no indicator of the utility of the findings for implementation in real socio-economic context, but many researchers regard asterisks as goals.

The confusion matrix paradigm is a good choice to illustrate a particularly troublesome question, one shared by many other methods for measuring human judgment, including those involving reaction time. Performance in these experiments usually depends upon some imposed "loading" of the observer, using supplementary tasks which are irrelevant to the main purpose. Loading is needed because otherwise an attentive observer, instructed to quickly identify the signals as they are presented, would hardly make any errors at all with the signals on current automobiles. If different signal systems were to be tried, for example, using green taillights, and this method of testing is used, one will probably find it impossible to tell the difference between the systems because there will be so few errors. Therefore, investigators load the observers with other tasks that divert their attention, or they make the environmental conditions so severe only marginal visibility of the signals would be possible. For example, mental arithmetic or perhaps a visual-tracking task might have to be performed continuously while the test signals are presented. Furthermore, the test signals would be given at unpredictable intervals, only for brief durations and somewhere off the central line of sight. In real driving, there is high sequential correlation of events. The observer can be scored for his performance in both the distracting task and in the principal task of recognizing signals.

Under these conditions, different patterns of confusion between one signal system and the other may well show up, but still not be conclusive because there is no good way of equating the stress level imposed on the operator in the laboratory with the distribution of stresses in real driving. Ideally, one would determine the critical level of perceptual or attentive loading that prevails in traffic and then conduct the experiment at the same level.

There is no easy way of telling whether observer loading in real traffic ever reaches the level that is required to demonstrate a difference between the systems in the laboratory.

Reaction time measurement is another common means for evaluating human performance. It depends mainly upon the biochemical propagation of impulses through the nervous system. The louder the noise and the brighter the light, the shorter the reaction time. It is hardly to be expected that subtle differences in configuration of signal lights would have any reliable or comprehensible effect on physiological reaction time as such, excepting insofar as these design differences also change the intensity of the stimulus.

The theory justifying the use of reaction time is that the operator has the advantage of a shorter distance in which to stop or maneuver if his reaction time is shorter. This is predicated upon a model of the human operator that regards him as an automaton that is supposed to respond immediately and invariably upon presentation of a signal. The model is obviously not a correct one since there is much more to driving than merely responding in reflexive robot fashion every time a brake light comes on. The light flashes, the foot pushes. A much better model of the human is a more complicated one that recognizes that the human actively processes the incoming information. View the human in terms of an information processor, connected to a memory, with a large repertory of possible actions—including among them, watchful waiting. Thus, when signals are given, the driver sizes them up in terms of his past experiences and the probable relevance they have to his immediate or expected status.

Headlights

The present headlight patterns were developed through considerable experience. But, since so much high speed driving is now possible on good roads at night time, there is a renewed interest in how to increase the illumination without excessive dazzle. Psychophysical studies are extremely expensive and time consuming because of the great range of human variability. So, we have taken a hybrid approach. We directly measure glare illuminance and target illumination, using the Pritchard photometer.

These measurements are related to Fry's formula for glare, which shows that the equivalent veil of light produced in the eyes by the oncoming headlights is greatly diminished if the line of sight diverts from the glare source by only a few degrees of angle.

The empirical photometric data are then applied to a simulated standard observer, instead of real subjects. It is a computerized embodiment of Blackwell's classic findings on detectability as a function of contrast ratio, adaptation level, and angular subtense of the target.

Despite the increased discomfort and fatigue, seeing distance is best maintained if both cars do not dip their lights. Unfortunately, neither Fry's nor Blackwell's data include any factors for the discomfort and fatigue produced by glare.

ANTHROPOMETRY: Visual Obstruction

The above discussion on driver vision emphasizes its physiological and psychological aspects; but the designer who determines the physical arrangement of the vehicle must be concerned with geometric considerations, such as the position of the driver's eye, in order to properly locate mirrors and structures which can otherwise obstruct forward vision. To do this, driver eye location must be known. The eye location of 2300 persons was measured photographically. The resulting statistical distribution of eye positions—in a coordinate system related to standard car body layout lines—was then converted into a Society of Automotive Engineers standard.

Whereas designers used to use a single point to represent the eye location, we now have a probability zone, with standard procedures for laying out sight-lines which will disaccommodate no more than specified percentages of the driving population, such as 1 percent, or 5 percent. The "eyellipse" is now referenced in a number of Federal Motor Vehicle Standards.

A corresponding probability region can be mapped on the instrument panel by projection from the eye position probability zone. Although the steering wheel is only a minimal obstruction for any one person, the statistical nature of eye locations makes it difficult to find an instrument panel area which is positively visible to nearly everyone, unfortunately.

There are some significant difficulties with devices such as the "eyellipses." Its use implies a rather inanimate driver, much as if he were only some static scaffolding to which a pair of stationary photocells were substituted for his eyes. That too demeaning view of the driver is especially apparent in the specification of field of view seen through the mirrors. The field of view available to the driver is considerably greater than that implied by the mechanical application of these techniques, because the range over which he can move his head without compromising his driving is fairly large compared to the size of the population eyellipse. That does not invalidate the use of these techniques, but it should be understood that there is no simple equivalence between what a driver can actually see and the field of view constructed by graphical methods based on such a device.

Interior Dimensioning

Standard devices have been established, again through the Society of Automotive Engineers—and these are also basic to the federal requirements—for standardized dimensioning of the vehicle interior. It is obvious that a standard reference point for interior dimensioning cannot be found in the structure of an upholstered seat, so it is provided for in a standard SAE device which is weighted and articulated in imitation of a vehicle occupant. It is used for measurement and for confirmation of design.

The designer, on the other hand, uses a flat version of that device—somewhat like a design manikin—as a design aid. These aids come in

10th, 50th and 90th percentile sizes. But these aids are not sufficient to fully determine package requirements. Therefore, direct anthropometric determinations must be made.

We are not interested in the usual anthropometric dimensions, such as arm length per se. Rather, we are interested in where the instrument panel must be placed so it can be reached, which is quite a different matter. These experiments are conducted to obtain the probability distribution of reach, and from that we establish a lower bound—such as the 5th percentile. It is significant that this kind of applied anthropometry is directed toward the vehicle, and not toward the operator. All coordinates are relative to the vehicle, which after all, is all that a designer has any control over.

The Classification of Package Types

Driver reach is determined not only by the anatomical characteristics of the person, but also by the package arrangement in which he must perform his driving task. His seat adjustment is determined, at least partially, by the relationships among the pedals and the steering wheel, and reach is further affected by the type of restraint he is wearing. There are at least 9 relevant parameters in addition to restraint configuration: steering wheel size and angle and its horizontal and vertical location relative to the accelerator pedal, the seat height and the back and pan angles, the seat travel and the distance between the pedals and the seat-track limits. These 9 parameters would have to be varied in an experiment if we want to know how far people can reach in different packages. For example, we might arrange these 9 parameters in a factorial experiment design with each of them only at two experimental levels, given us $2^9 = 512$ different mockups in which to determine arm-reach envelopes! Since each arm-reach experiment is a rather involved and lengthy process, this job is obviously impractical. Furthermore, only two levels for each factor is insufficient to adequately bracket the domain of package types anyway.

The problem is to arrive at a small number of prototypical test packages so the burden of experimentation can be contained within reasonable bounds, and so the experiment will provide maximal surplus information to allow an interpolative application to package types that are not included in the study.

Fortunately, the package parameters are correlated. If the seat is low, then it must also be located rearward to allow for a generous obtuse angle at the driver's knee. Because of correlation among the package dimensions, the effective number of package parameters may be reducible from the 9 parameters originally chosen to describe vehicle packages down to perhaps three or four underlying variables. These basic variables can then be used as a new way to describe the packages. It will obviously be easier to do an experiment in which only three factors are systematically varied than if all 9 of the original package parameters had to constitute the set of dependent variables in the experiment.

The analysis of package types to determine their underlying dimensionality uses the mathematical procedure known as principal component analysis, or in a somewhat different sense, factor analysis. The procedure starts with the table, or matrix, of intercorrelations among the package dimensions. The main result of the procedure is a new matrix with 9 rows just as the original one, each row corresponding to a package design dimension. Each column is a "factor," a new construct or continuum which underlies the correlations among groups of design parameters, and the entries are coefficents showing the degree to which each of the original design parameters are related to the new "factors." There are fewer "factors" in the solution than parameters we started with.

As entities, the factors are abstractions, but they will have some meaningfulness. The first factor will account for the greatest amount of variance in the multidimensional scatter of the original data, and will embrace the dominant aspects of what the variables have in common. It may be called "the" package factor, and will mainly reflect the general truck-vs-car character of the new continuum. The other factors will represent other aspects that are less prominent, mainly small departures in detail from the predominant trend.

Biomechanics

Biomechanics, or the investigation of human susceptibility to injury, still has some unresolved problems. For example—unlike the case for measuring human performance in driving—experimentation to establish the levels of force, or deceleration, that would be considered injurious cannot be done on representative samples of people. It must be done with animals or with human cadavers, which are of varying quality.

Furthermore, day-in, day-out product testing must be done with laboratory devices, not with biological materials. So these devices must be calibrated so they produce indications commensurate with actual injury.

For example, attempts are being made to develop standard laboratory impacters simulating human tissue. How can we measure lacerative potential, or puncture potential, in a way which produces a numerical reading, and which relates directly to real skin and real bones? These methods have been very valuable for qualitative evaluation of designs, but we must seek ways to develop objective performance criteria. However, there can be excessive concern over fidelity of simulation of the impacters. After all, it is the vehicle and its structure which is being tested, not the impacter.

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DISCUSSION

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Dr. Soliday joined the faculty of the School of Engineering at North Carolina State University in 1969. He previously taught in the Department of Psychology at Lamar State College of Technology in Texas. His background also includes several years of research at North American Rockwell Corporation in Columbus, Ohio. He holds a Ph.D. from Ohio State University in physiological psychology. His published research ranges from studies of performance deficits in subhuman subjects as a function of brain lesions to studies of human behavior involved in piloting planes. In addition to teaching in the area of human factors engineering, he is currently bringing his experience to bear on the analysis of the driving task.

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Dr. Versace's paper on automotive engineering research was most interesting. The ideas were stimulating and the data informative.

In his discussion of accident avoidance, he made the point that many contingencies exist in any driving situation, and that one or more of these can lead to sequences of events that can culminate in an accident. The driver is adaptable, which means that he can analyze and alter contingencies, and thus block sequences that lead to accidents. For example, he may reduce speed or swerve the vehicle to avoid an impending collision.

This approach makes the driver the key figure in accidents. Psychological factors such as motivation, perception, and intelligence become the factors that determine which of all possible sequences of events actually occur in a given situation. The picture has face validity; every driver has been in situations in which he must act so as to avoid undesirable situations.

However, there are also many situations in which the driver has insuffiicent time and/or knowledge to be able to act appropriately. These situations stem from factors associated with the vehicle being driven and from the environment in which the vehicle is being operated.

For example, mechanical failures such as brake and headlight failures can occur in situations which allow the driver no time to avoid an accident, while unexpected highway conditions, such as ice or other vehicles suddenly approaching from the rear or side of one's own vehicle, can also render the driver powerless. In all of these situations, the effects of the driver's perceptions, attitudes, etc., are minimal or non-existent.

More highly sophisticated warning systems might be able to tell the driver what is happening in many of these situations, e.g., a warning light might signal impending brake failure, or some kind of radar might detect in time a vehicle suddenly approaching from the side. These techniques would help to restore the central role in accident causal sequences to the driver and attention could be more legitimately focused on him. Of course, this would probably not be possible in many cases due to technical and cost considerations, and we would still need a model of the accident situation that accounts for factors associated not only with the driver but also with his vehicle and the environment that he and it operate in.

In his discussion of the problems of interpreting laboratory test results, Dr. Versace pointed out that we do not know how to relate task loadings in the laboratory to those found in actual driving. As he says, many times we merely increase laboratory task loads until significant differences are found, and then try to extrapolate the findings to the real-world situation. The extrapolation may or may not be meaningful.

The writer agrees wholeheartedly with this observation, and would like to add that another difficulty of interpreting laboratory tests stems from the fact that subjects taking part in laboratory studies are very much aware that the anxiety that accompanies real driving is absent. Most of them believe that this lack of anxiety makes the laboratory task much different from the real driving task.

Perhaps the difference simply lies in the fact that subjects are not as highly aroused in the laboratory as they are on the highway due to the lack of anxiety. However, the subjects tend to believe that anxiety itself is the important factor and frequently state that its absence reduces the validity of the results. Various techniques, such as using hypnotism or drugs, might help correct this difficulty.

At any rate, Dr. Versace has pointed to an important research area which is the establishing of meaningful relations between laboratory and real-world situations. Extrapolation from one to the other will have much greater validity when we know how to relate the two.

Dr. Versace discussed the use of reaction time measurement in evaluating performance efficiency. He noted that the idea behind the use of reaction time is that a driver who reacts quickly has more time to manipulate his vehicle than one who reacts slowly. He criticized the idea because it assumes that the driver is an automaton, which he clearly is not (at least, not always!).

Dr. Verace proposed that a better idea is one that views the driver as an information processor, an entity that evaluates various signals and acts on them in accordance with stored information. He does not state how the information itself is to be defined and measured in various situations. Since such definition and measurement are difficult and frequently arbitrary, some clarification of this point would have been desirable, as would have been the presentation of an illustrative study.

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