HIGHWAY RESEARCH RECORD

Number 265

Route Guidance

5 Reports

Subject Area

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Foreword

The five papers in this RECORD provide a comprehensive review of research and development efforts aimed at bringing about a literal highway-man-vehicular system. The description of a single project in the degree of detail presented here is an uncommon procedure for the Highway Research Board. However, such extensive development of a single traffic control or roadway guidance system jointly by the Federal Government and private industry is likewise uncommon. Implications of such a system will have a profound effect on the socio-economic-political structure of all highway-related organizations. The experimental route guidance system (ERGS) is a prototype and could be a fundamental building block for controlling and distributing the flow of traffic, particularly in metropolitan areas.

These five papers provide: (1) an overview of route guidance requirements, (2) an analysis of the needs and desires of drivers for routing information, (3) a methodology for handling the information demands on the highway network, (4) a system design for achieving route guidance, and (5) a technique for solving the information display-operator interface problem.

The first paper by a team of four Bureau of Public Roads' researchers provides an analysis of the route guidance problem. A delineation of the various human processes involved in trip generation and the consequences of failure of any of these processes is examined in terms of its effects on traffic flow and the probability of accident involvement. Normative solutions to the routing problem using static and traffic responsive routing systems are examined. The constraints existing on present guidance systems of maps and signs have led this team to propose a programmed effort to overcome such constraints. Intermediate results of that program are discussed by subsequent authors.

The second paper jointly authored by three psychologists and a traffic engineer presents an analysis of information requirements for ERGS, the effects of various solutions, and empirical predictive tests of driver acceptance of ERGS. The microscopic analysis does not consider an intersection in isolation nor does it provide a macroscopic network analysis. Rather, the problem of traversing intersections and highway networks is considered from the driver's point of view. A new generic analysis applicable to other geometric and signal control problems emerges. The acceptance studies employed a film-questionnaire technique which has been seldom employed by psychometricians, but which is essential for problems that provide both novel and dynamic concepts.

The third paper prepared by a California systems analyst delineates the problem of coding the large and unwieldy United States roadway network.

The coding rules take into account geopolitical boundaries within the United States, densities of intersections as exist and as projected during the next few decades, and the operator's ability to easily use the code. The format of a current existing intersection codebook is also discussed.

The fourth paper prepared by two automotive industry developers provides a discussion of an ERGS system design for effecting reliable two-way communication between the highway and individual drivers. The design employs vehicular and roadway processing equipment and antenna loops on each communicating vehicle and in each road lane. Design, operation and installation procedures for this operating engineering prototype are described.

The last paper provides a discussion of the development of an in-vehicle, head-up display compatible with ERGS information transmission requirements. Analysis of the human requirements, operational tests of a modified aircraft design and final fabrication of two separate head-up displays are discussed.

—Burton W. Stephens

Contents

Third Generation Destination Signing: An Electronic Route Guidance System

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This paper analyzes the problem of routing an automobile driver safely and efficiently from his origin to his destination. Present highway routing and navigational methods are examined in the framework of a systems analysis of the highway routing subsystem. In this context, the functions, characteristics, normative operation, and constraints associated with the present routing subsystem are delineated. The analysis traces the implications of removing three major constraints from the present highway routing subsystem. These constraints are (a) communications with drivers primarily exists as an "open loop"; (b) communication cannot be individualized but must be utilitarian; and (c) the highway and the automobile are separate entities.

Techniques for communicating with drivers, which would effectively remove present system constraints, are next examined and considered in the light of a fundamental analysis of the routing problem. Evolving from this analysis is a route guidance system concept and a plan for implementing the concept. The concept is characterized by these essential features: (a) individualized communication; (b) unambiguous information; (c) unique codification schemes; (d) capability for conversion to dynamic routing; and (e) compatibility with existing signing techniques.

The implementation plan for the concept consists of a multiphased research and development (R & D) program which is currently under way at the Bureau of Public Roads. Included in the program are major studies leading to the design of an electronic route guidance system. Following the design of the system a prototype system will be installed on an actual highway network for a thorough test and evaluation program.

•THIS paper provides an analysis of highway routing or navigational methods and procedures as they exist today. The functions, characteristics, normative operation, and constraints of routing methods are delineated. Several novel techniques for communicating directional information to drivers are examined. Synthesis of certain techniques combined with a fundamental analysis of routing has produced a route guidance system concept which is currently being implemented. An R & D effort transforming the system concept into an operational system will be outlined. If we consider all highway route marking signs of the prefreeway era as "first generation" and freeway era signs of today as "second generation," the resultant assembly of hardware and software components may be viewed as a "third generation" destination signing system.

During the current decade it has become most fashionable to conduct analyses of existing man-machine systems to determine how to make them more efficient or to

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determine whether man should be supplanted by mechanical or electronic functional analogs. However there are usually severe symptoms of disorder before either conducting such analyses or implementing solutions emanating from such studies.

Such symptoms appear to exist for vehicular traffic operations. Those of us who are keenly aware of the degree of system disorder include: the infrequent traveler to major metropolitan centers; the traffic engineer who struggles from day-to-day with the movement of vehicles in and out of such areas; the weekend traveler to his favorite recreation area, and those of us who have observed the minute-to-minute variations of traffic density from the sky. The evolution of highway transport has been so gradual that our nation of more than 100 million drivers has merely adapted with only an occasional discouraging word.

Such adaptation should not be unexpected since our present highway transportation system and its associated methods of construction and control are the result of a gradual evolution dating back to the Roman Empire's Appian Way. Nineteenth century English and American personal transportation was astonishingly similar to our present methods of routing and control. In London, safety officers performed the functions of adaptive signals at high-volume intersections. Traffic congestion in 1850 in New York City was often dissipated by the use of a policeman's nightstick.

About 1920, the motor vehicle became a practical means of extending the environs of most Americans. The problem of finding one's way became a reality for many drivers. Signing devised by various automobile clubs and local governments became a solution, or rather a myriad of solutions. Oil companies and auto clubs provided services to their customers and members in the form of maps and road signs of varying complexity. Various inventions such as Jone's moving map provided guidance to dirvers. The errors in planning and guidance were frequent, but the penalties of an error were usually minor.

Today the penalities are considerably greater, although we only now seem to be coming aware of the costs involved due to congestion and not easily finding one's way. Although the costs are intuitively perceived, they have seldom been measured. When they have been measured, greatly simplified assumptions have been made. Frequently we have seized upon solutions to a tremendously complex set of problems without knowing how to measure the efficiency of such solutions.

In this paper we do not attempt to provide a solution to traffic congestion problems nor do we provide a comprehensive theory of traffic movement. What we do attempt to do is the following: trace the implications of removing three major constraints from the highway transportation system. These constraints include the following:

1. Communication with drivers primarily exists as an "open loop";
2. Communication cannot be individualized but must be utilitarian; and
3. The highway and the automobile are separate entities.

The difficulties and benefits associated with removal of each of these constraints will be delineated in the context of a systems analysis.

The most striking benefit to the removal of these constraints added to "real time" measurement of traffic proficiency leads toward the possibility of distributing vehicular traffic much more uniformly than is possible with the present system of routing. Such a procedure is mutually advantageous to individual drivers and roadway authorities. This strategy has been labeled "route control" by Gazis (1).

A SYSTEMS ENGINEERING ANALYSIS OF ROUTE GUIDANCE

The specific system to be analyzed is a part of the highway transportation system. It is the collection of techniques, methods, procedures and devices which we will refer to as the routing subsystem.

Although activities involved with systems engineering will not be described here, some of the important steps will be delineated. There are several excellent books which serve as an outline for this endeavor; for example, see Chestnut (2), Flagle et al

(3), and Goode and Machol (4). Major questions that will be addressed in this analysis are the following:

1. What are the functions of the system?
2. How can we characterize the operating environment of the system?
3. What information do we possess about the system's current operation and how should it operate?
4. What constraints upon system design exist?
5. What tradeoffs exist between different proposed system solutions?

These questions will serve as an outline for analyzing the routing problem. The functions of the highway routing system are to provide "course and routing" information to be available to the controller at appropriate roadway nodes, and to provide error signals when an improper course is selected or to provide other adaptive controls if improper maneuvers are made at junctures. The functions should not be considered as independent. This will be shown to be the case for the proposed design discussed later in this paper.

These functions may be further delineated by specifying the operations involved in trip generation, incliding trip planning, path control, choice point path selection and control, and terminal or destination recognition. Each of these tasks presently demanded of the driver becomes more important as the trip becomes longer, congestion more variable, and the perceptual and cognitive capabilities of the driver are low or stressed.

Trip planning requirements are presently served by human memory, previous transferrable experience, and the ability of the driver to make accurate decisions regarding relative distances and durations associated with different routes. This latter information is derived primarily from maps, which also can serve to prepare the driver for certain static elements of the trip. Other information regarding construction activity or congestion on various links usually is not reliably available to the driver during the planning stages of "trip making."

In congested areas, frequent changes in routing may be necessitated by various levels of traffic demand. The driver who is very familiar with the highway network he is traversing has comparatively little difficulty in selecting alternate routes. However, even here he is placed in situations where memory may be taxed, his decision process rate exceeded, or information regarding the state of congestion on alternate routes simply is not available. He frequently becomes what we have labeled a "local stranger."

Path control primarily involves perceptual, information processing, and psychomotor control tasks that are related to judgments about overtaking, following, steering, accepting gaps between vehicles in the traffic stream, and passing other vehicles. The degree of interaction between the uncertainty associated with routing decisions judgments and vehicular control still remains a question to be resolved empirically, although some data have been obtained. Brown and Poulton's analysis (5) of spare capacity under various conditions of traffic load and intersection frequency and use of Sender's technique (6) of calibrating information load of drivers suggest that traffic density and highway geometry greatly influence the variability of psychomotor control.

More to the point is a simulation study of time sharing conducted by Stephens and Michaels (7), which, although conducted in the laboratory, indicated that proficiency of a simple tracking task similar to steering is greatly influenced by the amount of signed information along the roadway and the subject's expectancy for such information.

Field studies that directly measure speed and lateral variability as a function of the amount of destination information to be "stored in human memory" are now being conducted by Bureau of Public Roads' researchers.

Further, it seems reasonable to assume that increased stress or decreased alertness brought about by alcohol, fatigue or other causes will be augmented by environmental uncertainty. Compounded by destination information preserved by imperfect memory and difficulties in locating and recognizing signed information, it is remarkable that accident rates are not higher than currently reported.

The proficiency of executing the tasks associated with driving varies among drivers. Persons who have a great deal of difficulty in processing information regarding the highway environment appear to pace the task by decreasing their speed, hence increasing the variability in relative velocities of vehicles on the highway (6). Empirical relations between vehicular relative velocity and high accident rates for rural highway have been established by Solomon (8). A speed difference as low as -10 mph was reported to yield about six times the involvement rates, as when the vehicles did not vary from the average speed of traffic. Recently Cirillo (9) reached essentially the same conclusions regarding the Interstate Highway System, although the results are more dramatic. It is interesting that this relationship is not symmetrical, and the minimum involvement rate occurs with vehicles operating at speeds somewhat above the mean speed of traffic at large.

Choice-point path selection and vehicular control in the vicinity of highway junctures appear also to be greatly affected by difficulties associated with information processing, decision-making and psychomotor response changes. Mullins and Keese (10) indicated for freeway ramps that 0.72 accidents per million vehicle-miles (APMVM) occurred in the vicinity of off-ramps with 3.91 APMVM reported at on-ramps. The converse result was reported by Lundy (11) for California roadways. He indicates that off-ramp accident rates vary from 0.62 to 2.19 APMVM, while on-ramps produced from 0.40 to 0.93 APMVM. Different geometrics, signing and traffic volumes probably account for these differences.

Cirillo indicates a rapid increase in accident rates as one approaches the decision point at interchanges. Two miles to four miles before the juncture the accident rate is approximately half that of the area between the gore and 0.2 miles immediately preceding it for urban Interstate highways. Comparable rural Interstate sections yield only about an increase of one-half as one moves closer to the highway juncture.

Covault et al (12) attempted to determine the effects of lateral dispersion and speed changes in the vicinity of interchanges as a function of destination information redundancy provided via both "audio" and visual signs. As the redundancy of presentation was provided, hence increasing the probability of transmission of directional information to drivers, lateral stability and speed constancy increased.

Finally, as the driver approaches his destination, how does he know he has arrived? There is a rapid sequence of decisions associated with locating the specific goal sought by the driver. He must park, usually in such a way that he subjectively minimizes walking distance from his vehicle. In parking lots, on city streets and in the vicinity of shopping areas, the demands upon judgment are great. Probably due in part to the relative infrequency of making such judgments, subjective estimates of the distances involved during such maneuvering are markedly poor. There appears to be a cascading of decisions that demands both rapid judgments and consumes a substantial proportion of most trips. Current studies at the Bureau of Public Roads deal with the scaling accuracy and judgments associated with turning maneuvers, and distance judgments such as those involved in parking lots.

Since approximately 60 percent of trips are 5 miles or less in length (13), and final selection of a specific parking spot can occupy from about ½ to 2 minutes, a considerable proportion of the traveler's time is occupied in this latter task. We have estimated that from 2 to 24 percent of travel time is occupied in this latter task; and for the driver whose trips are almost exclusively less than 5 miles in length, the upper bound approaches 40 percent. We do not wish to imply that the terminal phase of travel is entirely constrained by routing information. Parking availability is undoubtedly much more important in reducing this time.

For the driver unfamiliar with the characteristics of the terminal, the problem becomes much more critical. The driver must search for cues relating to his destination that may or may not be prominent. They should indeed tell him when he has arrived. However, there is a period of intervening activity between assimilation of such cues and turning the motor off that bears careful scrutiny. Such empirical analysis is planned by Bureau of Public Roads' researchers using the information calibration technique devised by Senders.

The effectiveness of fulfilling the tasks that compose the highway routing subsystem depends largely upon the specific characteristics of the environment in which the drivers accomplish their respective trips.

Characteristics of the Operating Environment

The environment in which individual trips are generated is characterized by roadway segments, frequently composed of multiple parallel paths connected at junctures directly or by intervening roadway segments. For traffic assignment purposes, this more complex structure has been contained in the simpler notions of roadway segments (links) and intersections (nodes). When treated this way a variety of techniques can be applied to solve shortest route problems (14). Unfortunately, historical data of averages regarding travel patterns have little applicability to demands upon particular roadways at any specific time (except possibly those operating near "saturation").

It would appear that a far more microscopic analysis of trip distribution and its environment is in order. Consideration of at least the following roadway-related characteristics is required in order to successfully model the transition of vehicles from one set of roadway segments to another, or from their respective origins to their respective destinations. These include (a) vehicle's lane during the approach to each roadway junction, (b) conspicuousness of junction including signing, roadway delineation and highway alignment, as a function of distance from the junction, (c) geometric channelization in vicinity of juncture, and (d) signalization and other control techniques.

The extent to which each of the characteristics of the roadway facilitates or inhibits the flow of traffic depends in great part on the modulation characteristics of (a) traffic, i. e., the density and the flow characteristics; (b) pedestrian flows; (c) weather restrictions; (d) vehicle handling characteristics; and (e) driver perceptual sensitivities and response capabilities. Several microscopic models incorporating various combinations of parameters have been developed (15, 16, 17).

To say that microscopic analysis of intersection and interchange operation is required is not to say that network operation and corridor operation analyses are not required.

As pointed out earlier, the objective of route control is the distribution of vehicles on the roadway network to increase traffic flow throughout. To achieve this objective we must ascertain (a) the diversity of origins and destinations, (b) the time distribution of departure and arrivals, and (c) existence of parallel routes within various corridors. A discussion of anomolies of traffic operation due to various stressors is beyond the scope of this paper. It suffices to say that inclement weather, poor vehicular acceleration characteristics, high vehicular density, and driver capabilities all can influence traffic operation to a considerable degree. Perhaps the more salient question is, "How should traffic operate on the highway network?"

Normative System Operation

In the previous section many characteristics of the environment as they affect distribution of vehicles on the network were discussed. It is now necessary to define the system in general operational terms if we are subsequently to consider the effects of certain constraints operating upon the traffic environment.

Perhaps the most general characteristic of the total system operation is the degree of entropy it possesses. Entropy in this context may be viewed as the variation of flow on the totality of all roadways or links within the system. Hence we can define "traffic system entropy" as the sum of the variances of flow.

Obviously such a measure is conditional upon the time period over which measures of flow are gathered; hence, we may refer to yearly, monthly, daily, "rush hour," or entropy for any time period depending upon the purpose of our inquiry. For example, if we wanted to decide whether several signalization strategies for different daily time periods are warranted, flow should be measured on a one-hour or less base.

There are several advantages however to defining entropy in information theoretical terms. The major advantage is associated with the partitioning of information without regard to a metric (but not without regard to logic). Hopefully we may arrive at the same measure of information in several ways including the speed variability of pairs of vehicles and individual vehicles. Shannon's classic on information theory (18) has shown that logically variance may be transformed into information (or uncertainty or entropy)[1]. Using the same types of formulation, throughput may be calculated for individual intersections or extended to broader networks. Other formulations including conditional flow may also be developed.

It is beyond the scope of this paper to demonstrate analytically the relationships between various microscopic measures of information for vehicular traffic flow. It suffices to say that once the transformations between flow and vehicular speed and acceleration patterns are made, equivalence of different operations should provide equivalent results, although some estimation processes are more efficient than others. A separate paper establishing these relationships that provide tests of an information model is in preparation.

However, treated in such a context, the capacity of a highway arterial or network section may be considered as a maximal transmission or bandwidth problem. Such a scheme suggests decision rules for recommending alternate routes when flow approaches theoretical capacity. Nearly the entire impetus for development of improved routing techniques is to increase the existing level of service such that it approaches theoretical capacity.

The development of a proposed method for routing drivers through highway networks has been based upon partial analysis in the absence of sufficient flow data to effect more detailed analytic solutions. Network efficiency is obviously a macroscopic measure that does not treat minute variations in the system. It is meaningful to planners, designers and officials who are operating a traffic control system, but not to the individual driver who is primarily concerned with completing his trip quickly and reliably (19). So long as there is a monotonic relationship between these two criteria, no difficulty exists. Otherwise reconciling the two becomes an optimization problem.

One of the major steps in the development of the proposed routing system was a study by Carter et al (20). An attempt was made to develop a conceptual scheme for measuring the effectiveness of highway networks. Their approach was reductionistic and was greatly oriented toward driver benefits as compared to total network advantages. A section of this unpublished report is reproduced here to illustrate hypothetical relationships between certain of these measures.

> The criteria for effective operation of a highway network must be operationally defined in terms of level of service of the network, safety, and comfort and convenience to the operators. Values must accordingly be assigned to each of these criteria and finally alternate systems evaluated in such terms. One of the most difficult problems associated with such evaluation is how to optimize among criteria measured in differing terms. The evident answer lies in devising a common measure, or metric, to ascertain whether certain criteria which seem really important to the planner are actually important to the user. For example, a number of researchers have indicated that drivers appear to choose routes which provide time savings even though drivers might have to drive much greater distances. Hence it would appear reasonable to employ time savings in place of or in some weighted combination with physical distance over the network as a criterion of network performance, at least for a number of types of travel.
>
> Michaels (21) has suggested an even more comprehensive formulation which provides a common index of subnetwork usage. This measure incorporates branch distance (in miles), relative distances on high-design facilities and low-design

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[1]Each sample should be taken over a fixed time period (for example a 5-min interval). Maximum correlations might be obtained by applying auto-correlation techniques that permit us to estimate the delay associated with each juncture. The use of such a technique is open to question, however, since stationarity should be assumed for use of this technique. The delay itself probably should be treated as a random variable.

facilities and average travel speeds and distances. An equivalency measure can be established between these values and the level of stress impinging upon the operator. This provides for a scaling method relating certain of the variables associated with comfort and convenience.

For various levels of this measure, both the effect upon traffic operations (primarily in-stream turbulence and turbulence at junctures or nodes) and upon safety (the probability of collisions weighted for severity) must be determined....

The level of traffic or vehicular performance can be operationally dealt with at a molecular level. Turbulence has been operationally defined for the branch situation by a number of investigators. "Acceleration noise" (standard deviation of acceleration) has been employed for the in-stream case by several investigators. While this measure is gross it is becoming widely employed to differentiate various levels of traffic operation. Roeca (22) has developed a more comprehensive analytic technique for evaluating the effects of particular disturbances introduced into the traffic stream, (e.g., the effects of a stopped vehicle on the road shoulder upon in-stream speed variations)....

Molecular operation of vehicles at nodes has also been explicitly considered by Bureau of Public Roads personnel while at least two contractors, Covault (12) and Mace et al (23), have explicitly developed criteria for effective juncture in the traffic stream prior to the diverging operation as well as performance on the ramp itself.

Although we have little assurance in the relevance of such measures as those presented here, the absence of data makes it essential to develop certain hypothetical relationships between a meaningful measure of driver efficiency and network efficiency as a guide for further research. Let us take driver benefit to be the percentage of drivers taking the shortest temporal route from their respective origins to their respective destinations. Because of the difficulty of prescribing upper bounds for obtainable speeds on various highway segments, it is more meaningful to talk about the impedance of the highway system I (S).

Network impedance may be taken as the difference between capacity or maximum flow and the actual flow relative to the density on the highway link summed over all links in the network. If we could prescribe an upper speed bound, V (S), then system efficiency, E (S), might be taken as that speed less I (S), or simply E (S) = V (S) - I (S).

Although the scales are mixed (one ordinal, the other ratio), Figure 1 is used to illustrate the relations between network impedance as defined above and the percentage of drivers taking the shortest routes.

These relationships suggest that so long as "free flow" conditions are maintained, familiar drivers are not obliged to substantially change or reduce their velocities; they will traverse a route because of its intrinsic benefits. It is simply a preferred route. As capacity is approached on a particular link, average speed decreases. The driver

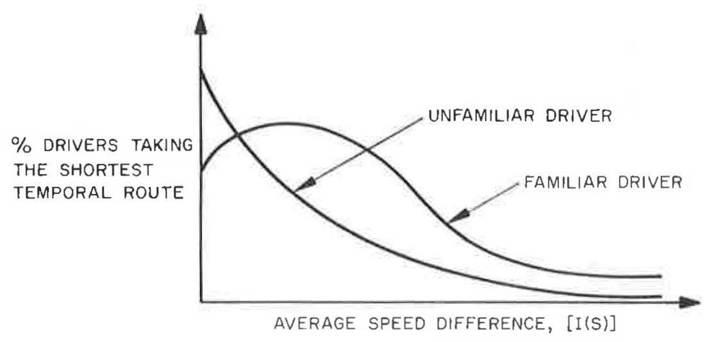

Figure 1. Relationship between driver benefits and highway system impedance.

"scans memory," receives radio communication of traffic conditions, or employs passenger knowledge and preference or maps in order to "rationally" choose alternate routing, hence improving his route selection. The "unfamiliar driver" who has not had the advantage of having traversed the route before has little to help him facilitate his travel. Hence there appears to be a monotonically increasing function between the driver benefit and network efficiency for unfamiliar drivers, but network efficiency would be less than maximal when unfamiliar drivers choose shortest temporal routes.

At least one more concept should be introduced into a generic analysis of network operation—the notion of the degree of adaptation afforded by the system dynamics. Traditionally this concept has had little place in the development of routing systems, although many instances of dynamic operation have been reported in connection with traffic operations within the past few years. Examples include several freeway surveillance and control systems (24), helicopter communication to drivers (25), and adaptive signalization techniques (26).

It behooves us to develop some notions as to the relative benefits when treating the system in either a static context, updating infrequently (e. g., during morning or evening rush hours) or providing "real time" data for updating best route solutions. A routing system which provides instructions to drivers based upon "best route" solutions derived from historical data will be referred to as a "static routing system." A routing system which provides instructions to drivers based upon data supplied by air and ground observers and other surveillance techniques with solutions updated frequently is referred to in the context of this paper as a "dynamic routing system." At the present time there is little advantage to providing routing information in that it can be used only to effect signalization schemes. Hence if we are willing to assume that such information can be used to increase the throughput at highway junctures as well as to direct drivers, it becomes a practical question apart from its theoretical significance.

One way of approaching this problem is to map system entropy into a measure of a benefit-cost ratio for each type of system. Total system entropy must be established or may be evaluated for subnetworks. Obviously each benefit and cost must be made operational and should reflect an extrapolation for some period beyond the initial installation. Benefits are assumed to be weighted cost functions or may assume another common metric such as that discussed in Michaels' article (21). The value of such a scale is not great unless it is either of the interval or ratio type.

A number of tradeoffs in selection of benefits must be made. In the highway field, the "bread and butter" in the transportation of people is the level of service afforded by various highway sections. Construction of additional freeway lanes is a costly process ranging upward to several million dollars per mile in some urban areas.

Deployment of system aids to guidance generally is assumed to increase linearly with system entropy although stepwise implementation seems to be a better extrapolation of the historical trend.

The benefits from any system of guidance, which are most salient to highway officials, include safety and efficiency of highway plant operation translated into construction cost reductions, reduction of hazardous appurtenances and lowered operating and maintenance costs. When levels of service fall below certain criterion values, new lanes, interchanges, parallel roadways and signalization systems usually result.

Other benefits accrue to the driver. Salient to him are stopped delays, time occupied with travel, fuel costs and stress. We have assumed a cumulative logarithm function for benefits. Its form can be given by:

$$B = a\left(1 - \int_0^x e^{-gx}\, dx\right)$$

where

a and g = weighting values;
x = the number of aiding units; and
B = the measure of benefit.

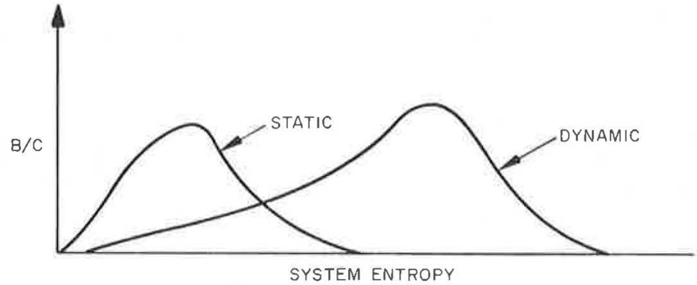

Figure 2. Roadway system value relations.

The costs have been assumed to be of the same form, only the weighting constant associated with the exponent is greater; which is to say that it becomes asymptotic more rapidly. The limit then of benefit-cost ratio (B/C) is a constant. When the B/C ratio is compared to system entropy, returns begin to fall off beyond some maximum value.

But such routing strategies do not allow us to be responsive to changes in traffic demand unless we alter routing based upon historical data or operate responsively to the minute-to-minute alterations in demand. One may wonder why we are not obligated to be responsive to low-flow, high-concentration conditions. The answer is simply that if we are aware of such persistent, obvious bottleneck conditions, they could be alleviated by new construction.

The initial costs for a dynamic system undoubtedly will be high with a less dramatic decrease in cost as engineering production increases. The benefits for a low entropy system should be about the same as a static system; but as entropy and impedance increase, the benefits should increase as a logarithmic relation. These conditions suggest more gradual increase toward a maximum when the B/C ratio is taken relative to system entropy. These system and individual value relations are plotted in Figures 2 and 3.

Benefits to individual drivers mainly continue to increase as a system of routing aids is implemented unless they actually have an adverse effect upon travel. His direct costs are fixed and indirect costs are nominal for the individual driver. Functions for static and dynamic systems are inverted-U shapes, however as system entropy increases rapid obsolescence would be expected. It is only in areas with persistently small populations that a truly static system could be expected to be useful.

Maximum B/C ratio for a programmed routing system undoubtedly lies somewhere in between the two prototypes described here. A truly static system will not have practical utility unless its rules are understood to refer to only one time period (non-rush

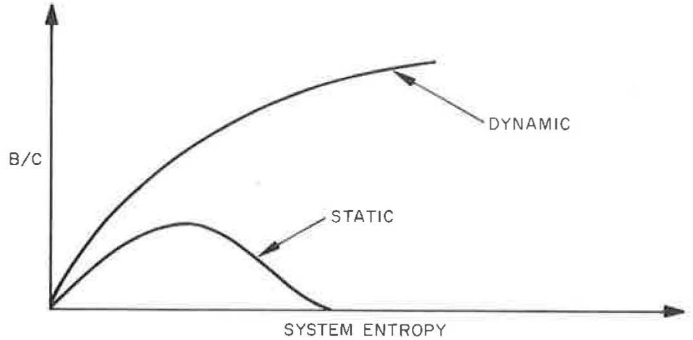

Figure 3. Individual value relations.

hour) or be employed only in areas where prohibitions do not change for daily time periods. Discussion in the remainder of this paper will deal only with the programmed type or a dynamic system.

System Constraints

Historically there have been a number of constraints on methods of providing good-quality, reliable highway navigational aids. These constraints might be loosely classified as either technological or socioeconomic. While many socioeconomic constraints markedly affect system effectiveness, they will not be discussed explicitly in this paper. Rather, this discussion will examine the principal technological constraints.

In the preceding section, it is hypothesized that the reliability and efficiency of traffic networks can be greatly enhanced by making the system dynamically responsive to individual user requirements. Furthermore, favorable benefit to cost ratios were depicted for a dynamic system deployed on a high entropy network. Let us now examine the major technological constraints on the present highway navigational system, which must of course be removed in order to provide a dynamic, user-responsive system. As indicated earlier these constraints include open loop communication, utilitarian rather than individualized communication, and the separation of roadway and vehicle components of highway transportation. Communication is "open loop" in the sense that information flows in one direction only—from the highway sign to the vehicle operator. There is no provision for the driver to make his destination known to the system, or in other words, there is no feedback channel in the system.

In any control system the consequence of open loop operation, with no feedback, is the requirement for very careful calibration of the system. In the case of the present route guidance system, this calibration is accounted for by the design of the sign message, which leads to another major constraint of non-individual presentation of routing information.

Information conveyed by signs must be designed for the traffic stream at large. Consequently, with sign messages it is inherently impossible to convey precise meanings according to individual driver's needs or destinations.

If a sign message does not conform to a driver's expectations or if he lacks good orientation, the result is hesitation and indecision at crucial decision points. Thus, accident potential is increased at decision points, and turbulence can be introduced in the traffic stream with resulting adverse effects on capacity. A wrong decision means extra travel and driver frustration. Also, there are documented cases of drivers backing down freeway exit ramps and performing hazardous weaving maneuvers after deciding they had made the wrong decision (27).

Another constraint on our present highway system is the fact that vehicles operating in the system and the operators of the system (i. e., highway authorities) are relatively independent of one another. In today's highway system this is manifested by the lack of direct communication links between the highway and the vehicle.

For example, Desrosiers (26) has shown that a considerable period of time elapses before vehicle operators adjust to a change in the speed of progression of a signal system. His research clearly shows the need for direct communication of the traffic signal setting to operators of vehicles using the system.

In summary, by removing the constraints on communications between vehicle and highway many benefits in areas other than route guidance could ensue. However, this paper will generally describe how a two-way communication system between the vehicle and highway benefit the route guidance function.

Techniques and System Solutions for Vehicular Routing

The number of techniques for communicating directional and guidance information to drivers has expanded as technology has grown. Early constraints have become less compelling as the economics of electronic circuits have become less restrictive from the user's point of view.

A brief look at highway signing methods and routing communication techniques permits a perspective that leads to solutions to highway routing problems that should be both economically feasible and socially acceptable.

Over the years, the art of highway route signs and marking techniques has changed tremendously. From the era of makeshift local directional signing and colored bands on poles to identify routes, it has progressed through the establishment of the "U. S. route" system and state route systems, to the Interstate System with its standard signing. Whether every change has been truly an advance is open to question. Color coding, currently being suggested in some quarters as a step that should be taken to promote smooth flow and safety, is characteristic of some of the earliest route markers.

A brief description of some of the most prominent methods of signing utilized or experimentally operated today follows.

Static Visual Signing—Today's signing attempts to privide the driver with destination and routing orientation. Occasionally he may choose, with the assistance of maps, one, two or three routes to a specific destination. Destination information (if it appears) on the sign does not necessarily relate to the driver's destination but may merely be another milepost to the driver's ultimate destination. The routes advised to the driver do not always take into account delays due to congestion and other transient events. These routes could be selected on the basis of shortest travel time, scenery, business, etc.

On high-speed roadways, signs must be massive to accommodate the driver but in doing so they create a driving hazard. In urban areas, signs may tend to be very small and difficult to read even at low speeds. Sign designers, however, do not take into account the variable visual proficiencies among drivers or the complicated maneuvers that often have to be performed. Thus signs are frequently not placed in an optimum location to aid all drivers.

Variable Message Visual Signing—In recent years variable message signing has been used to a limited extent. This type of visual signing attempts to take into account the delay due to congestion. By proper sensing equipment or by merely using a clock to indicate the beginning and end of peak periods, the delays could be indicated by some figure of merit and transmitted to the driver via a variable message sign to indicate possible alternate routes. Again this type of signing is merely an intermediate aid to the driver and does not take into account his ultimate destination.

Audio Signs—Studies in the area of audio signs have shown that advisory information regarding approaches to exits, obstacles, maintenance operations, traffic accidents, etc., can be transmitted to vehicles as they proceed down a highway. This system makes use of a prerecorded audio message that is continuously repeated at preselected points on the road. A roadside antenna, trigger loop and transmitter are employed as well as an in-vehicle receiver. This type of signing is conceptually similar in many cases to static and variable message signing. However, the system could be portable and could act as an early warning device for drivers as they approach hazardous situations. It is conceivable that information regarding alternate routes could also be prerecorded.

Several improvements and innovations to facilitate routing communication between the roadway and driver have been promoted during the past few years. Only the major techniques are given here.

Direct Inquiry Techniques and Maps—A driver today has several methods at his disposal for obtaining a routing to a destination. The familiar oil company maps used as planning devices and tourist services offered by oil companies and automobile clubs are the most common of routing assists given to drivers. In some areas he may also call a travel service if he is equipped with Citizens Band Radio. All of these methods still require the driver to search out the appropriate signs or landmarks.

Passive Communication Systems—In a passive system, the roadside equipment would continuously transmit coded signals concerning all destinations. The vehicle equipment would only accept that signal which corresponds to the encoded destination. The coded signal would also correspond to the type of maneuver to be performed at that particular intersection or trigger a particular message to be presented, whether it be visual or auditory, which advises the driver of the maneuver to perform. This system would require the bulk of the equipment to be housed in the vehicle. If a number of nodes are instrumented that are very near to each other, the problem of radio interference arises. Many frequency allocations would be necessary and these are almost impossible to obtain because the spectrum is fairly well utilized at the present time. Another disadvantage is that if the logic equipment is housed in the vehicle, this would mean that the responsibility of maintaining complex equipment would rest with the driver or vehicle owner. This is difficult to visualize from the condition of some of the automobiles on the road today. Discussion of an example of such a system may be found elsewhere (28).

Active Communication Systems—In an active system the vehicle transmits its coded destination to the roadside decoding equipment via a two-way near field communication link. Upon request from the decoder the in-vehicle transmitter is triggered to send its destination to the roadway equipment. The roadside equipment "looks up" the destination in a preprogrammed "best route" solution matrix or set of tables and sends the appropriate coded signal that corresponds to the proper maneuver to be performed at that particular intersection through the same communication link. The maneuver symbols or messages are activated in the vehicle by the coded signal, which triggers the appropriate display elements.

The bulk of the equipment is at the roadside. The in-vehicle equipment is simpler and requires less maintenance. Benefits are numerous with a vehicle active system; for example, it has built-in origin and destination study capability, traffic count data, traffic surveillance capabilities, etc. Also, use of a near field communication link requires a minimum of frequency allocations from the Federal Communications Commission. The best example of such a system is found elsewhere (29).

A PROPOSED ROUTE GUIDANCE CONCEPT

About two years ago the Bureau of Public Roads began to develop a new concept of route guidance. A number of studies had been concluded, or were nearing completion, which indicated positive benefits from a system that overcame some of the deficiencies of the existing route guidance techniques (12, 23, 28). Furthermore, there was no shortage of proposals from a variety of groups for plunging ahead with development of devices for directing information to drivers by various means. Though none of the devices proposed were actually complete route guidance systems, many of them had features that might be employed in a complete system. It was becoming increasingly evident that a comprehensive analysis and plan was needed to integrate previous research and to guide future work.

As a result of the integration of previous work and a thorough analysis of the problem, a proposed route guidance concept has evolved. Concept testing of a closed loop, individualized, integrated highway-vehicle communication system was carried out in the Washington, D. C., area. The results indicated highly significant improvements in travel time and stress reductions of such a system (30).

The system concept may be characterized by the essential features discussed in the following sections.

Individual Communication

To overcome the inherent limitations of highway signs and their messages to the traffic stream at large, it was deemed necessary that the route guidance system communicate information to individual drivers. This feature is justified by studies (6, 31) that have shown that drivers' control performance is facilitated when uncertainty is decreased. Study results suggest that when individualized communication is employed at freeway exit ramps, traffic operations should be significantly improved.

Specific Maneuver Information

To bring the drivers' decision-making requirements to an irreducible minimum it was apparent that information relating to the specific maneuver required to negotiate a choice point must be conveyed. Also, this information must be conveyed unambiguously to individual drivers. Therefore, the concept includes a requirement that the communication must terminate in the drivers' vehicle. This requirement, in turn, creates a need for an information display for the driver. The driver's display is the final link in the communication subsystem, and the information it emits is the basis for the driver's vehicle control actions. The design of the display is critical in that it is the major informational interface between the human operator and the highway-vehicular environment. A detailed analysis of requirements for relating displayed information to highway geometrics is given elsewhere (32).

Human factors analysis indicated that the best display technique available was the "head-up" display being used in low altitude aircraft. Kollsman Instruments conducted a feasibility study that eventuated in a vehicular head-up display prototype (33).

A parallel requirement, to that of providing specific maneuver information at a choice point, is the obvious goal that the sequence of choice point decisions add up to a "best route" to a driver's destination.

Unique Codification Schemes

Implicit in the route guidance concept that has evolved is the need for information coding schemes that are desirably efficient, flexible enough for other highway uses, capable of future expansion without disruption, and are compatible with state-of-the-art information handling subsystems, both machine and human.

A coding scheme for intersections that is compatible with best route solutions and that is human engineered to reduce short-term memory requirements is described elsewhere (34).

Optimization between efficient machine code techniques and human usage is required in the interface between address machine logic and the operator during the process of encoding. Philco-Ford addressed some of these requirements. Analysis of the problem is being continued by the Bureau of Public Roads.

Analysis of the character of directional codes indicates that links, nodes and link scalar quantities are not sufficient for high-quality solutions of best routes. Solutions of large networks having deterministic link scalars can be solved in reasonable periods of time using decomposition techniques. However most routing problems have relatively small stochastic link scalars as input data. This suggests more microscopic analysis will be fruitful.

In general, models of traffic flow using a combination of parallel links and sequential and conditional dependencies for selecting particular links at each node have not been formulated. It appears that high-quality solutions will depend upon a codification system yet to be devised.

Further, as a result of coding work accomplished thus far it is apparent that information coding goes beyond the route guidance concept and overlaps with several other important highway functions. Among these are urban traffic control and urban transportation planning. The present coding scheme will be the subject of continuing review and compatibility analyses will be made with other highway functions in mind.

Static to Dynamic Conversion Capabilities

In the earliest stages of development of the route guidance system, it was recognized that a static system would have limited utility. This is due to the fact that a substantial portion of highway travel is composed of repeat trips over familiar routes. For trips of this nature to receive any benefit it would be necessary to sense changing traffic and environmental conditions and change routings to provide best routes in a dynamic situation. Analysis in an earlier section provides the rationale for such a decision. Accordingly, one of the system design goals has been that any coding and hardware approaches must be capable of conversion to a dynamic system. Design of the system should provide for simple methods for updating preprogrammed stored tables at each instrumented roadway area.

Existing Signing Compatibility

Another feature of the proposed route guidance system is its inherent compatibility with existing guidance techniques. Present guide signs would have to remain in place during conversion to the new concept, but would not have to be changed in any way. After the new concept became widely implemented, existing signing could no doubt be reduced to the minimum that might be required for "back up" in the event of a system failure or for the fraction of vehicles or intersections that might not be equipped.

Warning and regulatory functions of present signs can also be handled by the proposed system. In fact, the concept will no doubt be able to handle some situations that are troublesome for existing signs.

One such example is the familiar "lane drop" situation at interchanges. With the proposed system a driver can be given an advisory lane change maneuver signal at any desired point along the highway. Properly placed, for traffic and geometric design conditions, such a signal could eliminate driver indecision and provide ample time for a merging maneuver. Closely related to the lane drop problem is the left-hand exit ramp, which can be handled similarly.

An example of a regulatory sign whose function can be served by the concept is the one-way street situation. Since the proposed guidance system would take into account one-way streets, drivers would get signals only for the proper direction. The problem is non-trivial in the case of streets that are operated reversibly during peak hours. In this case, the roadside logic can respond to the change in direction and, thus, relieve the driver of reading and interpreting reversible one-way signs.

A PROGRAMMATIC DEVELOPMENT EFFORT

No matter how superior the concept, without a program of R & D studies with reasonable levels of support, the effort of identifying a desirable roadway navigational system is merely a mental exercise. Development of such a program built on the findings of other investigators and inventive attempts at communicating with vehicles from the roadside has commenced. Considerable detail as to what to communicate, when to communicate and how to communicate has been presented and previous sections have hopefully indicated why we should communicate.

Guidelines for such an effort were developed in an intensive study of the highway coding and route recognition problem conducted at the Bureau of Public Roads in 1966 (20). Within six months, an R & D program was developed which incorporated:

1. A detailed analysis of driver information needs and rules for the optimal transfer of such information;
2. A coding requirement and format;
3. Development of a programmed routing system design for both roadway and in-vehicle hardware;
4. Construction and installation of a limited amount of hardware for test and evaluation; and
5. Conduct of a test and evaluation plan.

Such a plan was to serve as the nucleus of major study areas, but cannot be considered a program in itself. Time phasing and identification of the criticality of each step ensued. Since that time, 26 R & D functions have been identified.

Driver Information Requirements for Route Guidance

The first logical step for providing a highway guidance scheme has required development of a rational description of highway routing. No such scheme has to our knowledge been developed for signing applications in spite of the substantial cost associated with their uses; it is estimated that the cost of roadway signs has been in excess of $3 billion (20).

A generic language for highway routing applications has been developed by Serendipity Associates in conjunction with Alan M. Voorhees and Associates as part of an effort to define the navigational part of the driving task (33). Basically this is an information requirements study, but has been developed at a fair level of detail.

A practical consideration has evolved from the question of where, spatially, should information be presented to drivers. An analysis of information lead distance follows from work formerly conducted by HRB-Singer, Inc. (23). The practical question is where roadway hardware should be physically located with respect to highway choice points. Rules for such decisions are being formulated. Most of this work is based upon empirical analysis of the need for specific maneuver information. Such analysis is to be verified by use of vehicular stability measures.

Many factors influence the variability in responses elicited by different drivers, hence the influence of aging, stresses and specific information requirements of traffic and highway geometrics all are being studied.

Finally this task includes some prediction of human acceptance of a system whose design parameters are hopefully optimized. This portion of the study required that preference data be collected from a substantial population representing some cross section of drivers. Serendipity is completing such an analysis employing a unique form of questionnaire—basically a motion picture questionnaire technique.

All of this work will lead to development of a final routing configuration that is engineered for human use.

Attributes of Network Coding and Best Route Algorithms

As early as 1964, the Bureau of Public Roads recognized the pressing need for the development of a national standard system of coding highway nodes, equally available to all potential designers of electronic routing and highway communication systems. Philco-Ford, in cooperation with the Bureau of Public Roads, developed a computerized technique to solve the problem of routing an individual from any origin to any desired destination within a highway network (28).

A discussion of the uniqueness of the code and also the partitioning scheme for dividing up the highway network follows.

Uniqueness—Philco-Ford has developed a coding system and formatting technique for the unique identification of over 4 million intersections in the United States. It consists of a logically consistent technique for naming intersections and roads of a highway network.

Partitioned Sets—Due to the size of the existing and projected roadway network the following procedure was used for developing the code discussed above. The code had to properly identify the roadway network. To accomplish this a dual form of partitioning was established: first, geographic, so that locality can be described via the code; and second, hierarchical, so that selective transmittal of hierarchical information reduces the total information loading and handling requirements on the system. This is done by furnishing complete information about the network in the driver's immediate vicinity and less information concerning the network far removed from his vicinity.

Rapid Access and Updating—An algorithm, also developed by Philco-Ford (28), allows a solution of a matrix to determine optimal routes on a highway network. Optimal routes can be described by various criteria such as travel time or distance.

Use of such a code in a programmed routing system requires three matrix solutions, i. e., for the two peak and the off-peak periods. However, in a dynamic system, solutions are needed more frequently so as to take into account delay, congestion, weather, etc.

Therefore, a system for rapid updating and access must be developed for the dynamic system. Algorithms are yet to be developed to determine optimum real-time solutions for alternate routes in a network.

Hardware Design

Based on the route guidance concept that had been described and the "best route" algorithm and network coding of Philco-Ford, work was begun on the design of hardware to implement such a system. General Motors Corporation has fulfilled this function in the program and an engineering model is now operational. Their report (29) gives details of the system design and only the general features will be described here.

The system design includes both vehicular and roadside components. The vehicular components serve the function of encoding the driver's destination, transmitting the destination to the roadside components at an intersection, and displaying the correct maneuver symbol or message received from the roadside.

The roadside component functions are to receive the driver's destination code, decode the destination in terms of a specific maneuver symbol or message and transmit maneuver information back to the vehicle. Roadside decode logic is based on stored programs that are developed from solutions to the best route algorithms mentioned earlier.

Communication takes place through simple loop antennae mounted under the vehicle and buried in the pavement in each intersection approach lane. During the period (0.03 sec or less) when the vehicular antenna is within the field of the buried road loop (generally corresponding to the road loop's physical boundaries), "destinations" are transmitted and maneuver instructions are received. Thus, each vehicle is specifically and individually serviced by the system.

Testing and Evaluation of System Effectiveness

The route guidance system is being proposed as a means of improving the safety and efficiency of the entire highway transportation system. Obviously the implementation of such a system would require large expenditures on the part of highway authorities and road users. Before a decision to implement such a system is made there must be a sound and convincing demonstration that the expenditures can be justified; or in other words, do the benefits justify the costs?

To provide inputs for a benefit-cost analysis an elaborate test and evaluation program is being planned. The goal of the program is to evaluate the effectiveness of the system from the driver's point of view, and from the highway authorities' point of view. Thus, the system evaluation plan consists of two distinct types of tests. Another way of classifying the tests is in terms of the level of detail or preciseness in measurement of some of the variables. In this context tests have been classified as macroscopic and microscopic. The matrix in Table 1 lists some of the more important tests that are planned for the test and evaluation program.

Plans for conducting these tests call for a network of approximately 100 intersections and about 50 instrumented test vehicles. The test network will be in one portion of a large metropolitan area. Some tests will be conducted entirely on the instrumented network, others may involve test runs in other non-instrumented portions of the area. Network characteristics and driver characteristics and driver population will be selected to make the tests as representative as possible. Travel characteristics such as trip

TABLE 1

HIGHWAY SYSTEM BENEFITS

Driver Benefits	Road Benefits
(a) Macroscopic Tests	
Time savings due to best routes and reduced errors	Minimize overall travel time
Fuel savings	Efficient use of network
Reduced accidents	Reduced congestion
Reduced information stops	Reduced air pollution
	Less congestion due to accidents
	Reduced roadside hazards
	Reduced accidents
	Improved aesthetics
	Reduced signing requirements
(b) Microscopic Tests	
Reduced operator stress	More efficient use of highway network due to decreased turbulence at decision points and higher overall speeds
Improved vehicular control due to reduced uncertainty	

length, trip purpose and time of day will also be considered in the design of the experiments.

The test and evaluation program is being designed to produce definitive data on benefits that can be expected from a static route guidance system. In addition, the test network is being selected to provide several configurations where dynamic system concepts can be evaluated. All costs associated with equipping and programming the network and test vehicles will also be developed. Thus it is hoped that the results of the test and evaluation program will serve as inputs to a comprehensive benefit-cost analysis. The ultimate objective of the program is to determine the feasibility of wide-scale implementation of the system. Such implementation would of course take into account developments of related systems for aiding the driver.

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Driver Information Requirements and Acceptance Criteria

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The purpose of this study was to analyze the route guidance information required and preferred by drivers. Required driver information was derived by determining how an unfamiliar driver negotiated a generic intersection. The generic intersection was defined in terms of (a) choice points, (b) characteristics of the approach to the choice point, and (c) characteristics of exit paths.

A driver's task analysis was performed to obtain estimates of time and information required to negotiate complex intersections. This enabled a determination of driver information requirements directly, from the step-by-step task analysis, and indirectly, from the estimates of information lead distance requirements. Driver information was established for approach paths, choice points, target paths, and close sequential choice points. Literature on human capabilities and limitations was reviewed to develop display concepts appropriate for a wide spectrum of the driver population.

Driver acceptance of the ERGS concept, information requirments, display characteristics, and desirability of a partially implemented system was also analyzed. Representative complex route guidance problems together with variations in the driver information requirements and display concepts were presented to drivers. The drivers indicated how they would perform with the displayed information, and which of the displayed information concepts they preferred. Finally, information on driver's preference for implementing the system on primary roads, in central business districts, at critical intersections, or in suburban areas was determined.

•THE Electronic Route Guidance System (ERGS) is based on a concept (1, 2) for furnishing a driver with individual information inside his vehicle that would enable him to accomplish a trip to his specific destination efficiently and safely. The role of this study in the ERGS development program is to identify the driver information requirements, determine the optimal display characteristics for the required information, and evaluate user acceptance of this particular method of furnishing route guidance information.

DRIVER INFORMATION REQUIREMENTS

The basic approach employed (3) in this analysis was to define the relevant factors that influence information requirements within an electronic route guidance system context. Initially, a distinction was made between trip negotiation, as conceived of in an ERG System, versus that under current route guidance methods. Current route guidance systems (highway route numbers, mileage signs, street names, maps, etc.) furnish information aimed at all drivers; the information is necessarily incomplete and presented intermittently, and the system relies on the driver to integrate it with his

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desired destination and make his own decisions at each choice point. ERGS, on the other hand, is conceived of as a way of computing and presenting the proper choice to each driver at every instrumented choice point or intersection, based on his specific destination. Thus, within an ERGS context, trip negotiation is defined as the process of efficiently getting a driver through a choice point or a series of choice points.

To understand this distinction, it was necessary to identify and define all of the relevant components of intersections as related to choice point decisions. Once having described an intersection as a choice point or series of choice points, it was then necessary to define as precisely as possible the driver's task related to the negotiation of those points. Consideration was given to those tasks directly influencing information requirements and those relating to lead distance components, such as lane-changing and speed-changing maneuvers. It was necessary also to identify the relevant response time factors as related to the capabilities and limitations of drivers in performing the driver task. These time factors are obviously important in the derivation of information lead distance requirements. Furthermore, the driver's tasks were oriented around the behavior that would characterize an unfamiliar driver, that is, a driver who knew neither the route nor the other characteristics of the roadway. The assumption is that the information and lead time necessary for an unfamiliar driver to negotiate an intersection efficiently will also be appropriate for all other types of drivers. This assumption was further modified by considering the unfamiliar driver with limited capabilities (that is, poor visual characteristics, and/or other limiting sensory-psychological factors), thus establishing a basis for the identification of maximum information requirements and lead distance components (3, Appendix C).

In the process of analyzing the driver's task, two task elements emerged as most relevant for the determination of information lead distance. These elements are changing lanes to prepare for a maneuver and changing speed to perform the maneuver. At an intersection, the lead distance for the initial information can, thus, be determined as a function of the requirement to change lanes and the requirement for the slowest possible exit speed from the choice point. These factors are influenced by other limitations imposed on the unfamiliar driver in light of speed, vehicle characteristics, environmental considerations, and other generic network characterisitcs. Therefore, the determination of information lead distance for a specific choice point took all of the above factors into account.

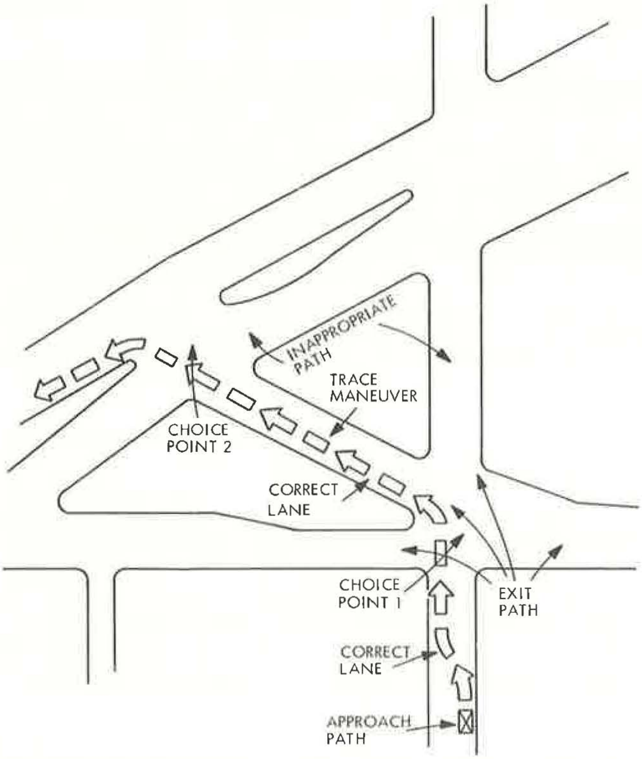

Figure 1. Components of an intersection for ERGS illustrating two close sequential maneuvers.

The next step in establishing the information requirements was to re-examine the driver's task and information requirements for a specific network in light of lead distance factors. The reason for this is that the lead distance required by a given choice point has within it the potential for generating additional driver information requirements. Specifically, as lead distance for one choice point increases, there is also an increase in the number of intervening choice points that could be considered potential exit paths for the driver.

Finally, the information requirements that had been identified through analysis were verified in the user acceptance study.

Definition of Intersection Components

For purposes of the ERGS study, intersection components or characteristics are defined primarily in light of the way in which a driver traverses the roadway where there is a choice point, or "nodal gore." This is in contradistinction to conventional intersection classification schemes, which are generally based on features obvious from a plan view rather than on the factors that affect driver behavior and information requirements. The classification scheme (Fig. 1) is oriented around the path components that are legitimate considerations to the driver approaching a choice point, as follows:

1. Approach path—the lane or lanes available to traffic entering the intersection or choice point.
2. Choice point, or nodal gore—the point at which a driver can choose between two or more exit paths, any one of which is available for travel by him. This does not include the choice between two lanes of the same approach, although drivers often must choose between two or more lanes to execute correct maneuvers.
3. Exit path—any path of one or more lanes leading away from the choice point.
4. Target path—the correct path beyond a choice point, for a specific driver-destination combination. Target path is distinct from exit path in that it may define a specific lane on the exit path.
5. Inappropriate path—a competing exit path near, at, or beyond a choice point that may appear to a driver to be the one he is seeking.
6. Trace—the path a vehicle would follow from an approach lane to an exit lane.
7. Sequential choice points—any series of choice points that occurs in sequence and that requires a corresponding series of maneuvers (close sequential maneuvers) by a driver to follow a specific trace.
8. Correct lane(s)—lane(s) permitting efficient and legal negotiation of the choice point. Correct lanes may be identified for the approach path, the choice point(s), or the target path.

Driver's Tasks at an Intersection

To determine the information drivers require in the way of route guidance at an intersection, one must first determine what a driver does at an intersection. The general tasks were limited to those perceptions, detections, and executions that are specifically required to negotiate intersections (Table 1).

The driver's task in the ERG System was developed around the concept of an unfamiliar driver (i.e., the driver who is making his first appearance at a given intersection). If the system can adequately guide this unfamiliar driver through the system, then all other drivers can use those portions of the displayed information that satisfy their particular needs.

The two primary components that were sought in developing the driver's task while nego-

TABLE 1

DRIVER TASKS IN INTERSECTION NEGOTIATION

1.	Perceive presence of route guidance source.
2.	Perceive potential path change requirement.
3.	Perceive approach path maneuver requirement, i.e., lane change.
4.	Execute lane-changing maneuver.
5.	Perceive specific guidance direction.
6.	Perceive approach path maneuver.
7.	Perceive need to change speed.
8.	Execute speed change.
9.	Detect node (put intersection into perspective).
10.	Detect end of route.
11.	Detect inappropriate path(s) on approach.
12.	Detect conflicting oncoming traffic.
13.	Detect obstruction in or near roadway.
14.	Determine need to stop.
15.	Stop auto.
16.	Detect target path.
17.	Detect inappropriate paths at choice point.
18.	Perceive choice point maneuver.
19.	Execute maneuver at choice point.
20.	Detect close path sequence.
21.	Execute close path sequence.
22.	Perceive target path verification.

tiating a generalized intersection were those that had an impact on driver information requirements and those that affect information lead distance.

The information requirements are affected by the following conditions:

1. It is a partially implemented system; therefore, the existence of instrumentation at the given intersection must be brought to the driver's attention.
2. There may be a requirement to change lanes in order to effect the intersection on a multiple-lane, one-direction roadway.
3. The lead distance required to effect major intersections might be such as to have competing roadways prior to the intersection.
4. The guidance information presented is on an advisory as opposed to a command basis; therefore, the driver must attend to current traffic regulations.
5. There are certain close choice points in a trace that may require multiple guidance messages to be presented prior to actual trace negotiation.
6. The next intersection or choice point could, in fact, be the destination desired by the driver.

The driver tasks do not take into account the initial input of destination information, route, or the selection of route type that might be preferred by the driver. Not all tasks are applicable to all choice points, and some tasks may have to be repeated on certain traces; for example, lane changing where there are more than two lanes in one direction.

Information Lead Distance

The lead distance calculations are based on estimates of the times required by drivers with a wide range of capabilities to perform the tasks involved in negotiating an intersection.

In establishing information lead distance from a choice point, it also is possible to identify requirements for close sequential maneuvers. This is done essentially by establishing the maximum lead distance for the required worst case maneuver, and determining whether this distance would extend beyond the prior choice point(s). If it does, then successive maneuvers are required, since the ERGS information must be provided before the previous choice point. Thus, in the application of the information lead distance requirement from any choice point, we may (in fact) establish additional information requirements, such as close sequential maneuvers, lane requirements beyond a choice point, and identification of conflicting inappropriate paths at or beyond a choice point.

The worst case condition for lane changing is the one in which the driver is in the worst possible lane under heavy traffic volume condition, and going at the maximum speed for the roadway under consideration. The worst case condition must also take

TABLE 2

INFORMATION LEAD TIME AND DISTANCE REQUIRED FOR WORST CASE-WORST DRIVER LANE-CHANGE MANEUVER

Function	Time (sec)	Average Speed (mph)	Distance (ft)
Lane change			
Detect ERGS present	2.5	40	147
Detect right lane required	2.5	40	147
Detect need to change lane	1.9	40	112
Detect aft car	5.5	40	323
Detect cars in right lane	5.5	40	323
Wait for acceptable gap			
Initial deceleration	1.63	35	84
Waiting speed	25.5	30	1,125
Change lanes	4.5	30	198
Total			2,459

TABLE 3

INFORMATION LEAD TIME AND DISTANCE REQUIRED FOR WORST CASE-WORST DRIVER SPEED-CHANGE MANEUVER

Function	Time (sec)	Average Speed (mph)	Distance (ft)
Speed change			
Turn right guidance	1.9	30	84
Red light ahead	3.8	30	168
Rule out prior path(s)	1.9	30	84
Slow down and stop	4.9	15	147
Total			483

into account the requirement to change speeds at any given choice point. The worst case condition is deceleration from the maximum speed on the approach to the safe speed for the most difficult turning maneuver at the choice point. Once these have been established, the time factors for the limited capability driver effecting these tasks must be developed.

Table 2 presents a list of tasks for the lane-changing maneuver. The lane-changing maneuver has many components relative to acquiring the forward, aft, and side positions of potentially competing vehicles. These occur after the driver has perceived the need to change lanes. He must not only determine the position of competing vehicles, but also their velocities relative to his own and to the path of interest. In addition, a driver must wait for an acceptable gap (3 Appendix D) to occur before maneuvering into the desired lane. On a multilane road, these tasks must occur for each lane change.

The speed-changing maneuver (Table 3) requires that the driver put competing vehicles along the approach into perspective. Obviously there is a need to insure that a following vehicle is not so closely behind that a decrease in speed will create a hazardous situation. Furthermore, the position and velocity of vehicles on the immediate side and front must be taken into account. Finally, the maneuvering times relative to whether the speed change is one of deceleration (the more normally anticipated maneuver at a choice point) or acceleration must be taken into account.

Driver limitations and capabilities were examined (3, Appendix C) in terms of the driver's ability to perceive, detect, and respond to events in the roadway that are critical to the driving task. Specifically, these ranges of capabilities, as they relate to task times, were applied to driver tasks for lane and speed changes.

Generic network characteristics affect information lead distance to the extent that they influence vehicle speed and the driver's visual task load. The most relevant characteristics are the number of lanes in the approach path, special turning lanes or lane prohibitions, and, of course, the number of possible exit paths at a choice point.

Applying these factors, the maximum possible lead distance for performing the lane change to the left and stopping maneuver for choice point number 1 on the generic intersection was calculated. It assumed a truck merging left; traffic density of 1,000 vehicles per hour; approach speed of 40 mph; an aged driver with long perception, decision, and maneuvering times; and poor visibility conditions on a wet surface. The serial analysis of worst case-worst task time makes it immediately clear that an excessive amount of lead time is required. If one differentiates between the information lead time required for lane changing, and that for speed changing, it can be seen that lane-change information is required at 2,459 feet, while speed-changing information is required at 483 feet, for a total of 2,942 feet.

This is based on a series of operations always using the worst case data. This is probably unrealistic and an answer to this particular problem requires further study. However, the above calculations suggest that it would be desirable to present lane-changing information to all drivers at all choice points, at the maximum information lead distance, unless this information could be presented at the prior intersection.

The information requirements at three points in the trace maneuver of Figure 1 on the approach path, at the choice point, and while negotiating close sequential choice points are depicted in Figure 2.

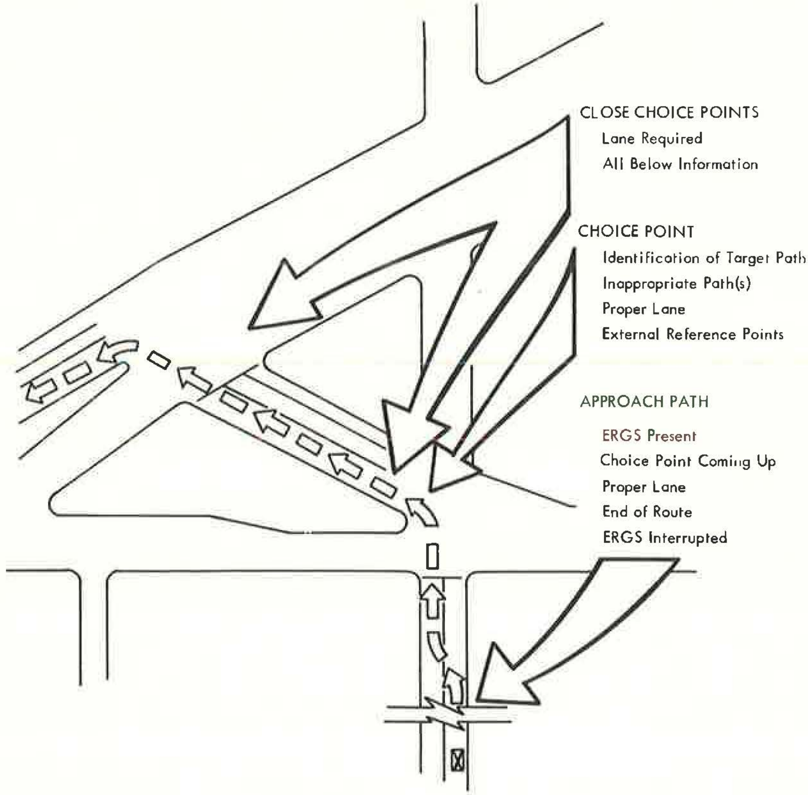

Figure 2. ERGS driver information requirements illustrated for a close sequential maneuver.

USER ACCEPTANCE STUDY

A user acceptance study was conducted to determine the general acceptance of this type of guidance system, identify the types of roads where it would be most useful, and verify some of the information requirements and display concepts that had been generated. The approach was to explain ERGS by means of a film, and to use the film to ask questions and an associated questionnaire to record answers.

Data were collected with the film/questionnaire "Guiding Tomorrow's Motorist" from audiences at the History and Technology Museum of the Smithsonian Institution. More than 1500 persons completed the survey questionnaire. Stringent exclusion of inconsistent and incomplete responses resulted in a sample of 561 that was used for the analysis (Table 4).

System Considerations

Ninety-four percent answered in the affirmative and four percent were undecided when indicating whether the Electronic Route Guidance System is desirable. ERGS symbols and words were preferred to conventional signing, 84 percent answered yes, 15 percent didn't know and only one percent indicated that ERGS was not better than conventional signing. Despite the apparent favor with which ERGS information was viewed, respondents were more reserved when asked whether they would buy ERGS equipment. Only 43 percent indicated that they would, 39 percent were undecided, and the remainder (18 percent) indicated that they would not. An indication of the relationship between need for the system (frequency of getting lost) and acquisition is shown in Figure 3. It is obvious that those people who get lost frequently would buy the system.

TABLE 4

RESULTS OF ERGS PUBLIC ACCEPTANCE STUDY
(Sample = 561 Licensed Drivers)

System Considerations	Yes	Don't Know	No
ERGS good idea	94%	4%	2%
Public buy	43%	39%	18%
Better than signs	84%	15%	1%
Cost Consideration		Would Buy	
	Yes	Don't Know	No
	$149	$221	$248
System Implementation	Most		Least
Highway connecting suburbs and downtown	37%		3%
Interstate connecting cities	23%		32%
Downtown shopping and business	24%		20%
Suburban shopping and business	7%		5%
Suburban residential	4%		22%
City residential	4%		18%
Information Requirements	Yes	Don't Know	No
Lane change	87%	6%	6%
Inappropriate paths	75%		25%
External signs	92%		8%

Display Consideration	Preference
Placement:	
Head-up (on windshield)	78%
Dash-mounted	22%
Lane-change information:	
Sound alone	1%
Sight alone	37%
Sound and sight	28%
Warning tone and sight	34%
Arrows vs words for lane changing:	
Words alone	3%
Arrows alone	15%
Both	81%
Optional routing solution:	
Safer routes	26%
Least time	63%
Least cost	2%
Most scenic	9%

Figure 3. Relationship between frequency of getting lost and system acquisition.

Cost Considerations

Respondents were asked to indicate their estimate of the cost of in-car equipment enabling them to use the ERG System. As shown in Table 4, the average cost estimate for buyers was $149, for non-buyers it was $248, and for those who were undecided, $221. Taking the sample as a whole and without reference to whether or not ERGS equipment would be bought, the cost estimate was $195.

System Implementation Considerations

Given the following choices—downtown shopping and business areas, city residential areas, suburban residential areas, suburban shopping and business areas, Interstate highways and highways connecting suburban areas and downtown areas—respondents most frequently indicated that ERGS routing information would be most useful on highways connecting suburban areas and downtown areas (37 percent). On the other hand, urban and suburban residential areas were not favored as locations for installation of the system. Downtown shopping streets and highways connecting cities were regarded by some as desirable locations, with nearly as many in each case.

Lane-Change Information

The majority of respondents felt that lane-change information was necessary (87 percent). Only six percent felt that lane-change information was not necessary, and six percent were undecided.

Identification of Inappropriate Paths

Respondents were asked to indicate their preference to two symbols that provided turning information at an intersection. One symbol showed the correct path in green and the incorrect paths in red. The other showed only the correct path in green. Seventy-five percent of the respondents preferred the symbol showing both correct and incorrect paths for turning information.

External Signing

Respondents were asked whether they preferred to have exit information from an expressway presented solely in the car (for example by being told to "take the third left") or whether they preferred a combination of in-car information keyed to external signing (for example, by being told to take "ERGS 4" where ERGS 4 was indicated by an external sign). The overwhelming majority of respondents preferred the combination of in-car information and external signing (92 percent).

Head-Up Versus Dash Display

The majority of the respondents preferred display of ERGS routing information by means of a head-up display rather than by a dashboard display. Respective percentages for these two answers were 78 and 22 percent. Those who indicated they would buy ERGS preferred a head-up display even more than non-buyers, with 84 percent indicating this preference. Aged drivers also showed a marked preference for the head-up display.

Method of Presentation of Lane-Change Information

When asked to indicate their choice between four possibilities for presentation of lane-change information—namely by sound alone, sight alone, sound and sight, or a warning tone and sight—almost no one preferred sound alone (only 1 percent of the sample). Thirty-seven percent preferred sight alone, 34 percent preferred a warning tone and sight, and 28 percent indicated that they preferred sound and sight. Interestingly, while sight alone was most frequently preferred by the total sample, the most frequent choice by buyers was a combination of sound and sight (40 percent of buyers). Another large percentage of buyers indicated that they preferred a warning tone and sight (36 percent). Also with increasing age drivers tended to select both sound and sight. It therefore appears that the majority of buyers would prefer some combination of sound and sight for lane-change information.

Presentation of Lane-Change Information

Respondents were asked whether they preferred messages composed of arrows alone, words alone, or a combination of arrows and words. The majority (81 percent) indicated a preference for the latter choice, while 15 percent preferred arrows alone and only 4 percent preferred words alone.

Basis for Optimal Routing Solution

Initially, the ERG System will probably not allow those with implemented vehicles to vary their basis for route selection (i.e., safety, scenery, etc.). To establish a routing criterion, respondents were asked to state the basis upon which they generally selected routes. The options were safety, least time, least cost, and scenic value. The majority (63 percent) opted for routes that take less time. Second choice was safety (26 percent), followed by scenicness (9 percent) and cost (2 percent).

DISPLAY CONCEPTS

The final step was to develop display concepts from:

1. The analytically derived and acceptance study verified driver information requirements for negotiating intersections.
2. An analysis of other ERG System display concepts that have been developed to this stage.
3. Public acceptance of various display concepts determined from the film questionnaire.

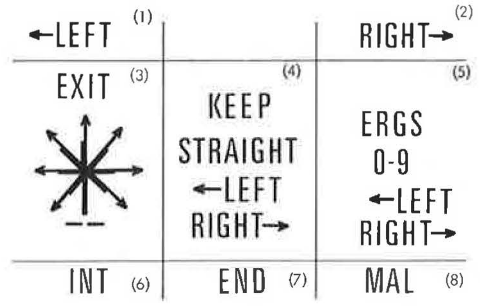

Figure 4. Route guidance information display concept (circled numbers are not in the display concept but related to text).

4. A design driver resulting from an analysis of driver capabilities and limitations. The design driver is an aged individual with inherent perceptual limitations related particularly to visual acuity and accommodation. The design driver's characteristics were used to establish presentation principles. The rationale for taking the aged driver was the fact that there are more than 13,200,000 people over 60 years of age who currently drive (Automobile Manufacturers' Association, 1968), and a display designed around the limitations of such a driver should be clearly within the capabilities of more able drivers.

5. Establishing a priority for display concepts that could readily accommodate multiple intersections under conditions requiring close sequential maneuvers and limited antenna placement due to cost constraints.

The concept finally developed would be feasible in both a head-up version (projected on the windshield) and a panel version (on the dashboard), with minor differences between them. However, perceptual characteristics of the aged driver, specifically his inability to shift from roadway tasks to panel display and back to the roadway, strongly supports the head-up display (5).

Key advantages of the head-up display are (a) presentation of information directly in the field of view of the motor vehicle operator, and (b) information is focused at infinity, which reduces requirements for adjustment in convergence. Thus, the head-up display presents information with minimal distraction from external visual tasks.

Figure 4 shows the display concept. At any given intersection only elements required to depict the route guidance message would be illuminated (Fig. 5). Along the approach path the information requirements are (a) the fact that a choice point is coming up, (b) the proper lane for the choice point, and (c) information on whether ERGS is interrupted, malfunctioning, or at the end of the route. The display concept could handle "choice point coming up" in the head-up version by merely presenting the required information, but for the panel display an auxiliary auditory tone or cue for the proper lane is required because the information may not be in the direct field of view of the driver whose attention may be focused on the operations in the roadway. Designation of the proper lane on the approach path is handled on the top line of the display by the words "right" (1) or "left" (2) with appropriate arrows. Arrows and words add redundancy, minimize uncertainty, and were preferred in the acceptance study. Since an ERGS interrupted "INT" (6) message or an end of route "END" (7) would normally be responded to last in any guidance message, this information is presented on the last line of the display. END is shown in red as an indication for stopping and INT in yellow indicating caution and need to revert to other means. MAL indicates system malfunction and is red (8).

At the choice point, the driver is given information enabling identification of the target path as well as inappropriate path information (3). The target path is identified by means of a green arrow on any one of seven equi-angular radials (excluding 180°). These radials provide sufficient flexibility so that the driver can perceive the target path in a manner close to the way that he would perceive the path through the windshield. The appropriate or target path and inappropriate paths are both shape and color coded. The appropriate path is presented by means of the leg <u>to</u> the choice point, and a leg with the appropriate arrowhead <u>beyond</u> the choice point is presented in green. The inappropriate paths are presented as red radials half the length of the path presented for the choice point with no arrowhead characteristics. In addition to inappropriate paths at the choice point, inappropriate path information for one intersection prior to the choice point may be presented. Because it is an inappropriate path it is depicted by means of a red dashed line. An "EXIT" indication (6) for portraying the route guidance command to "EXIT" on Interstate or grade-separated roadways is also presented. The exit word is presented in green above the symbolic configuration for the choice point.

In addition to information on choice point, target path, and inappropriate path, an important feature is the need to show the proper lane at and through the choice point of interest. This information is provided by means of the center portion of the display (4), where the driver can be instructed to keep straight, keep to the right or keep to the left. (Obviously the driver would only receive one of these three commands.) Because lane-change information is required both on the approach path and beyond the choice point, a convention was adopted to code lane-change information in a single color: aviation yellow. By providing lane-change information for the path after the choice point, the probability that the driver will have time to respond to a completely new instruction for the next maneuver is substantially increased. The reason is that normally the maneuvering required to get in the proper lane on the road to effect a subsequent maneuver takes planning, gap acceptance, and other factors requiring substantial lead time.

The display also provides the possibility of fairly complicated sequential maneuvers beyond the initial choice point by means of the information displayed in the right-hand side of the display (5). The display has been designed around the requirement to provide external signing, which is necessary for multiradial traffic circles and some complex interchanges and intersections. It is also consistent with the public's desire to have numbered exits when leaving the Interstate system. Since a 0 to 9 numeric can be presented with the words "right" or "left," it is possible to tell the driver to take

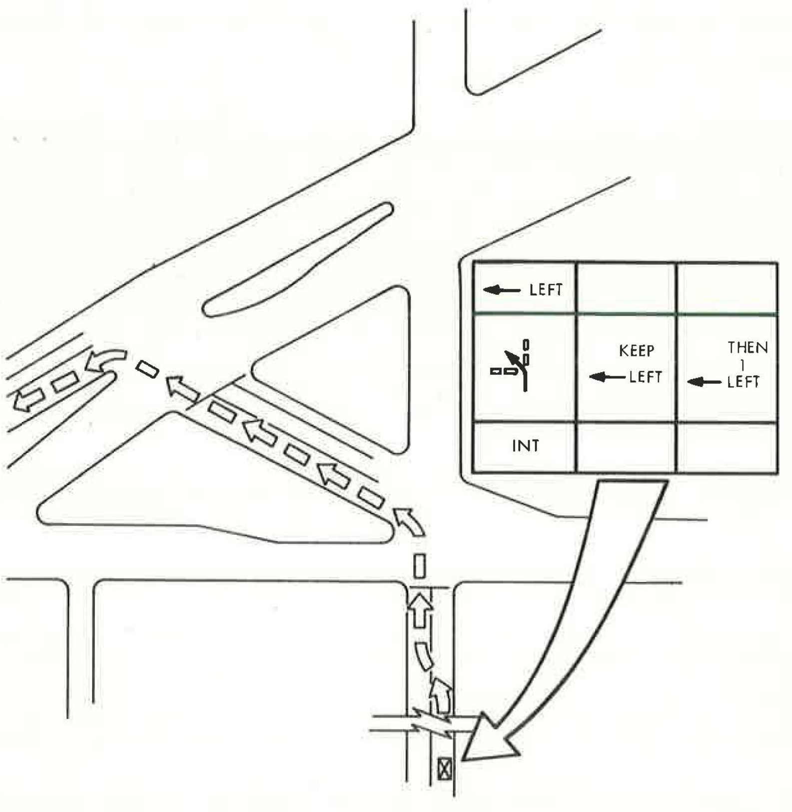

Figure 5. Application of route guidance information display in an intersection illustrating close sequential maneuvers.

up to the ninth right or left. However, it is not recommended that such an approach be applied. Actually to require drivers to take into account more than two streets is probably beyond their capabilities. Both the decline in short-term memory capability of aged drivers and the design goal of keeping complexity and uncertainty to a minimum require a better method of handling such situations. Therefore, if more than two streets have to be accounted for during close sequential maneuvers, which do not permit a new display, then external reference signing using the ERGS 0 to 9 configuration should be applied.

Accordingly, it is recommended that external signs be considered for situations such as traffic circles where more than two streets must be passed before the maneuver can be effected. If the exit from a traffic circle would occur prior to passing two streets, then first or second right or left, depending on the circumstances, would be more appropriate than the reference signing. The reason is that the driver entering into the circle may not have time to perceive the ERGS external reference signs but can readily count up to two streets. The external reference signs should say "ERGS" and not "EXIT," to maintain a distinction between them and the many exit signs already in use on highways. It is recommended that the information for the close sequential maneuver be given in green because it is related to choice point behavior and should be coded in the same manner as the exit symbol for the first choice point.

The last informational bit required is whether there is a malfunction in the system. To handle malfunctions, there is a system status indication that would normally indicate when any part of the system is malfunctioning.

The display presents information that is position, shape and color coded with sufficient redundancy for perceptual ease by the aged driver taken as the design reference point. It provides all of the information necessary to efficiently negotiate complicated close sequential maneuvers in a manner requiring minimal interpretation and memory, and enables the driver to know where to navigate his vehicle at all times in the route negotiation task. It also provides primary status information for the system as well as interrupt conditions and attainment of destination. An application of the display is shown in Figure 5.

SUMMARY

In summary, the driver information requirements derived from an analysis of an unfamiliar driver's task in negotiating an intersection were verified by the public acceptance study. The public thought the system was useful and a substantial portion thought they would acquire the in-car system which they thought would cost under $200.

A route guidance display concept designed around the limitations of an aged driver and the driver information requirements was developed. The concept is based on presenting a clear and unambiguous display of the essential maneuvers required to negotiate close sequential choice points (intersections). The analysis would suggest the use of a head-up display.

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Highway Coding for Route Designation And Position Description

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A coding system compatible with the Experimental Route Guidance System (ERGS) concept has been devised for application to over 4 million highway intersections of the contiguous United States. The derivation of this coding system involved suitability for hardware implementation, acceptability to the general driving public, and capability for the ancillary functions of highway data record files generation and processing. In addition, computer programming of an optimal route determination algorithm was accomplished.

The coding system developed utilizes a dual form of partitioning: (a) geographic so that locality can be described via the code; and (b) hierarchical so that selective transmittal of information based on highway network hierarchy reduces the total information load on the highway-vehicle communication link by orders of magnitude. Further, the code is alphabetic so that the code name is short, easily read and manipulated by the general driving public, thus inspiring confidence in its use and encouraging acceptance. The basic five-letter code substitutes a two-letter state abbreviation prefix for the first character of the code as used by the public, thereby establishing a first-order level of familiarity. Where possible, the code alphabet is made vowel-heavy so that generation of pronounceable syllables is enhanced. The resultant verbalization characteristic aids the short-term memorization process and tends to reduce human error in driver manipulation of the code.

A comparative cost analysis showed that the expected increase in hardware cost is only 2.65 percent over that of the minimum cost binary coding system. For the purpose of testing prototype models of the information exchange equipment, a FORTRAN IV computer program for solution of optimal routes on a network of 1,500 or fewer intersections was written and tested. Additionally, data processing formats for computer files of highway records utilizing the developed code were devised and applied in the construction of intersection files used for the publication of a United States Intersection Directory.

•OVER the period of years in which the present vehicular roadway system has developed from a simple roadway system to the current maze of complex interconnecting, sometimes three-dimensional network of streets, roads, and highways, the performance and quality of vehicles and roadways have improved, seemingly without corresponding improvement in highway guidance. The external (to the vehicle) visual signals that served to guide oxcarts and buggies over their routes are still with us today in a state of proliferation that matches the growth of the vehicle roadway system.

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Our present state of the art in highway signing is unsatisfactory from a number of standpoints, particularly in regard to route guidance. First, external visual signals are network-oriented and not driver-oriented. Road signs giving guidance information tersely indicate where the road goes, not where the driver is to go, forcing the driver to have preplanned his route and have some foreknowledge of the roadside signing to expect in the vicinity of network areas where he must maneuver in order to negotiate the network maze throughout his trip. Second, only a small portion of the total roadside signing is pertinent to a given driver's trip, resulting in a high degree of superfluity, but the driver cannot indiscriminately reject all road signing without the risk of rejecting that which is pertinent, forcing almost continual surveillance of signing along the route driven. This aspect of vehicle guidance serves to create anxiety and stress in drivers, probably contributing to driver fatigue and creating incipient hazardous conditions. Third, external visual signals are impaired whenever visibility is impaired, as in night driving, bad weather, and the obscuration of thick traffic or large vehicles.

Recognizing the need for a vehicle guidance system to suit the needs of the individual driver, the Bureau of Public Roads with Philco-Ford Corporation and other contractors has engaged, over the past three years, in a research project aimed at circumventing the problems associated with present vehicle guidance systems. Within the Department of Transportation, this project is referred to as the Experimental Route Guidance Systems (ERGS).

ERGS may be considered to consist of three main constituents:

1. A system of route coding logic along with application to the U.S. Highway network. This route coding involves the development of a logically consistent technique for naming intersections and roads of a highway network. For the purposes of this paper, intersections are called nodes and their emanating paths are called branches. Quantitative observations have determined that the vast majority of nodes have eight or less branches, so that a clockwise numbering of branches from 1 to 8, starting from the north as 1, would suffice as a coding scheme for node branches. Branch and node coding can provide an efficient language for designation of any point in a highway network, and hence any point of interest to a traveler. Application to data processing of highway records is also apparent for a coding logic such as developed here.
2. Development and compilation of files of optimal routes between node pairs on the coded highway network. Several algorithms exist for solving for the shortest route between two points in a network. The size of the network and the requirement for the shortest routes between all pairs of network nodes are vital considerations in the selection of the most appropriate technique. The technique chosen for handling large networks mathematically with ease in programming, small core requirements, and rapid solution, was a modification of the Shimbel "minaddition" algorithm.
3. Development of an information exchange methodology. The methodology developed takes place in three steps. First, by use of the developed coding logic, the driver informs the system of his destination. Second, the system selects from the files of optimal routes developed by the modified minaddition algorithm, the instructions to give the motorist so that he may proceed along an optimal route. Third, the instructions must be transmitted to the driver, transformed, and usably displayed. The system element that performs this function is further divided into two subsystems—the vehicle subsystem and the node subsystem.

It is the first two constituents of ERGS to which this report is addressed.

ROUTE CODING LOGIC

Viewing a segment of the U.S. Highway network schematically (Fig. 1), each node can be uniquely identified by a name or code (for this simple case a single alphabetic designator), and each branch emanating from the node, by a single numeric digit. The scheme for choosing the digit to identify the node branch is to assume that eight equiangular sectors (45 deg each) surround the node. Each of these sectors is numbered from 1 to 8 clockwise, starting with 1 as the northernmost sector. The branch is

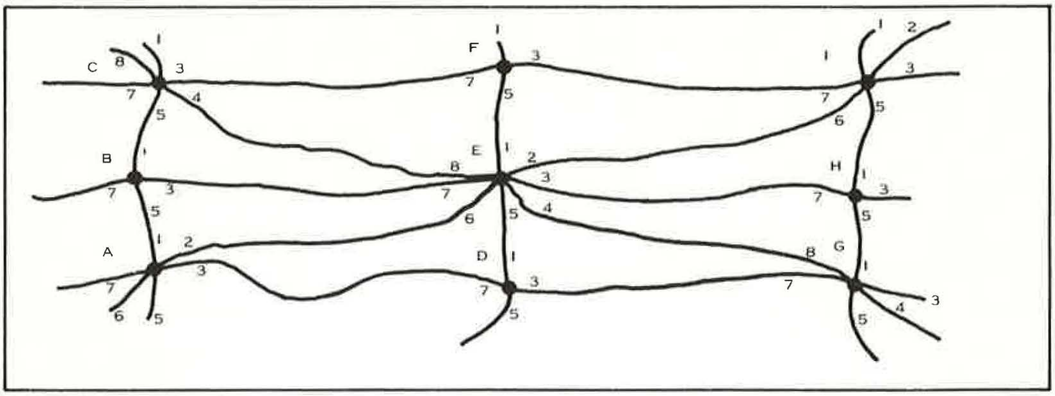

Figure 1. Schematic of segment of U.S. Highway.

identified with the number of the sector in which it lies as it first leaves the node. Complex nodes having more than eight branches can be identified as multiple nodes having separate and unique node code identifiers, each having eight or less branches.

With this basic coding logic, route following can be accomplished by designating the node code and the branch to be taken out of the node as travel across the network occurs. Thus, in Figure 1, if node I is a trip destination and node A is an origin, the route from A to I may be specified as A-3, D-3, G-1, H-1, I. Another routing may be specified as A-1, B-1, C-3, F-3, I. A third routing may be specified as A-2, E-2, I. If all branches of the schematic network are measured for distance, then it becomes possible to describe minimum distance routes from each node in the network to every other node in the network. Route measurements other than distance may be used and minimized in order to determine an "optimum" routing. Trip-time on branches may be minimized. If toll charges on some roads are encountered, then costs may be minimized. Whatever the criterion, optimal routes may be determined and stored at each instrumented node, so that each suitably equipped vehicle may indicate its destination as it approaches an instrumented node, and receive from the node appropriate information regarding the correct maneuver (turn right, turn left, continue straight, etc.) to perform in order to reach its destination optimally. Figure 2 shows the ERGS system's sequential operation.

Network Partitioning

The immense size of the U.S. Highway network, which is projected to contain approximately 4 million nodes within the next score of years, requires some form of subdivision or partitioning in order to reduce the networks to a tractable level for analysis and operations. A dual form of partitioning has been chosen for coding purposes, consisting of geographical partitioning on the one hand, and hierarchical partitioning on the other. Geographic partitioning is particularly convenient since it permits locality or place information to be imported via the code; hierarchic partitioning was found to be necessary in order to reduce the total information load on the system.

For ERGS coding, three hierarchic levels were chosen. The first level called the "primary" network level consists of the principal arterial roads in the United States similar to the Federal-Aid Primary System of highways and its intersections. The second level, called the "secondary" network level, consists of secondary roads similar to the Federal-Aid Secondary System of highways, its intersections, and the primary system. The third level, called the "minor" level, consists of all other roads and intersections connected to the other two levels.

By surveying current road maps of the U.S. Highway System and counting the intersections of the principal arterial roads, approximately 7,500 primary nodes were identified. In order to afford room for expansion of the highway system, allowance was made for 10,000 primary nodes. Each primary node is unique to a given geographic

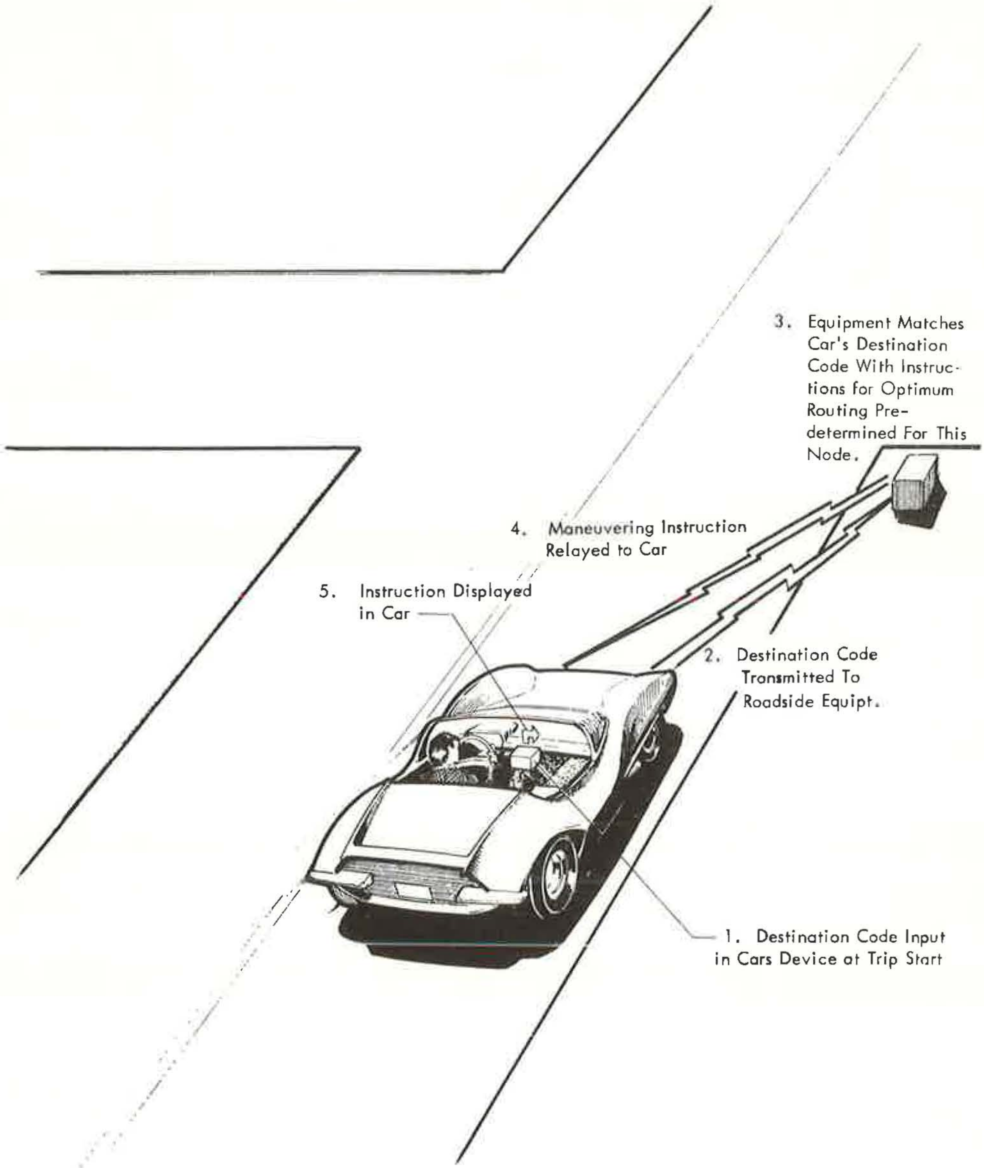

Figure 2. ERGS sequential operation.

partition called a "sector," thus defining some 10,000 geographic sectors for the United States. Within the geographic sector, allowance is made for including up to 20 secondary nodes; each secondary node being unique to a geographic partition called a "zone." Thus there is the capability of containing 200,000 secondary nodes in the U.S. Highway network (20 secondary nodes for each of 10,000 primary nodes). If, in a similar fashion, allowance is made for up to 20 minor nodes for each secondary node, or 20 minor nodes per zone, there would be the capability of containing 4,000,000 minor nodes in the U.S. Highway network (20 minor nodes for each of 200,000 secondary nodes). Three levels of network hierarchy can thus serve to identify in excess of 4,000,000 nodes.

Code Symbology

The problem next addressed in the route coding logic involves the selection of an appropriate symbology to be used in coding or naming each of the 4,000,000 nodes described by the three hierarchic levels. This aspect of the problem impinges upon two important factors in route coding: (a) equipment factors, and (b) human factors.

From the standpoint of equipment factors, the selection of a code affects the hardware items required to represent the code symbology in terms of input hardware, conversion hardware (from the code symbology to bit representation for the electromagnetic link between the vehicle and the roadside equipment), and data processing hardware, not only for the look-up process at the roadside equipment, but also for the maintenance of highway descriptive data files and the solution of optimal routes from any given highway network. Obviously, simplicity of the code will be reflected in the simplicity, reliability, and cost of the hardware representation of the code.

A simple example illustrating some of these factors is that of using the binary system for a node code, and the representation of a binary code with toggle switches. First, in order to have sufficient scope, at least 22 toggle switches would be required, since $2^{21} < 4 \times 10^6 < 2^{22}$. The binary representation of the number 4 million is

1111010000100100000000,

and 22 toggle switches would have to be set up to identify any one of 4 million nodes. To represent four million nodes decimally would require a seven-place input device, such as

4000000,

and a hardware representation of seven ten-place switches would be required.

The binary hardware implementation requires 22 "switches," each capable of representing two states, while the decimal hardware implementation requires 7 switches, each capable of representing 10 states. The binary coding system requires 22 x 2 = 44 hardware elements, while the decimal system requires 7 x 10 = 70 hardware elements. Note that the number of hardware elements is equal to the product of the number of switches, or input positions, and the number of states each position represents (the base of the number system used in the coding scheme).

Algebraically,

$$Z = B^m \tag{1}$$

where

Z = number of hardware elements required;
B = base of numbering system used in coding scheme; and
m = number of switches or positions required to represent the number in the code.

And, to satisfy the constraint that at least 4 million nodes be coded,

$$B^m \geqq 4 \times 10^6 \tag{2}$$

The question as to whether there is some combination of B and m which minimizes Z can be approached analytically by setting the derivative of Z with respect to B equal to zero and solving for B. Thus, solving for m in Eq. 2 in order to have the required scope of 4 million nodes,

$$m \ln B = \log (4 \times 10^6) \tag{2a}$$

substituting Eq. 2a in Eq. 1,

$$Z = \ln (4 \times 10^6) \frac{B}{\ln B} \tag{3}$$

Differentiating Eq. 3,

$$\frac{dZ}{dB} = \ln (4 \times 10^6) \left[\frac{\ln B (1) - B \frac{d(\ln B)}{dB}}{(\ln B)^2} \right]$$

$$\frac{dZ}{dB} = \ln (4 \times 10^6) \left[\frac{\ln B - 1}{(\ln B)^2}\right]$$

Setting the derivative equal to zero and solving for B,

$$\ln (4 \times 10^6) \left[\frac{\ln B - 1}{(\ln B)^2}\right] = 0$$

$$\ln B - 1 = 0$$

$$\ln B = 1$$

Therefore, B = 2.718. . . , the base of the natural logarithmic system. Substituting this value for B in Eq. 3,

$$Z = \ln (4 \times 10^6) \left[\frac{(2.718. . .)}{(\ln 2.718. . .)}\right]$$

$$= 15 \; \frac{(2.718. . .)}{1}$$

$$= 41,$$

which is the minimum number of hardware elements capable of being used in a hardware implementation of any coding scheme. However, control and display hardware is not available for use with base e numbering systems.

Base Comparison

Table 1 compares some of the base numbering systems and their associated symbology which may be considered for candidate coding schemes. The left-hand column lists the base of the numbering system, and the rows illustrate how the number "4 million" would appear in that base. The topmost row (the heading row) indicates the number of places (from right to left, the conventional way of going from low-order to

TABLE 1

RADIX-SYMBOLOGY COMPARISON FOR CANDIDATE NODE CODING SCHEMES

Base	Places																						No. of Elements
	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	
BASE																							
2	1	1	1	1	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	44
3									2	1	1	1	2	0	1	2	2	2	2	0	1	1	42
4												3	3	1	0	0	2	1	0	0	0	0	44
5													2	0	1	1	0	0	0	0	0	0	50
6														2	2	1	4	2	2	3	0	4	54
8															1	7	2	0	4	4	0	0	64
10																4	0	0	0	0	0	0	70
16																	3	$\overline{13}$	0	0	0	0	96
16																	3	D	0	9	0	0	96
26																		8	$\overline{19}$	$\overline{15}$	4	4	130
26																		I	T	P	E	E	130
45																			$\overline{43}$	$\overline{40}$	$\overline{13}$	$\overline{10}$	180
45																			↔	Δ	D	Δ	180

high-order numbers) required to represent the number "4 million" in the symbology illustrated. The extreme right-hand column gives the number of hardware elements (the product of the radix and the maximum number of places for the symbology chosen) required if the given radix is chosen for a coding scheme.

Several observations are possible based on the presentation of Table 1. First, any symbology was rejected if it did not read high to low order from left to right, as is conventionally done. Second, arabic numerals and english alphabetic characters are the only serious contenders for the choice of symbology to be used in coding. Third, although it has been proven that the base e will have the minimum number of hardware elements (41), it was not considered a candidate because there is no convention for base numbering systems with other than a whole integer base, and e is irrational. From the standpoint of fewest number of elements, the choice would appear to be between the binary, ternary, and quaternary systems, with the binary system probably favored because of the preponderance of hardware currently available based upon the binary numbering system. However, there are certainly more factors to consider than just the number of hardware elements. Popular acceptance of a coding scheme requiring the recognition and manipulation of 22 digits for each node would be practically nil. Consequently, human factors considerations must certainly come to the fore in the selection of a node coding scheme.

Human Factors Considerations

There is a considerable body of research which has been conducted relative to the psychological acceptability of a symbolism used to represent information. Cited

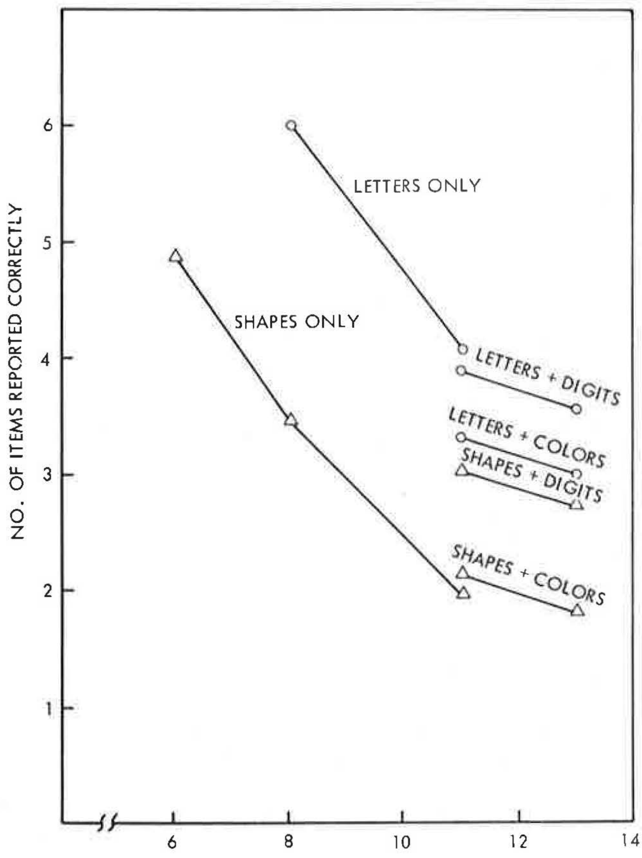

Figure 3. Recall capability.

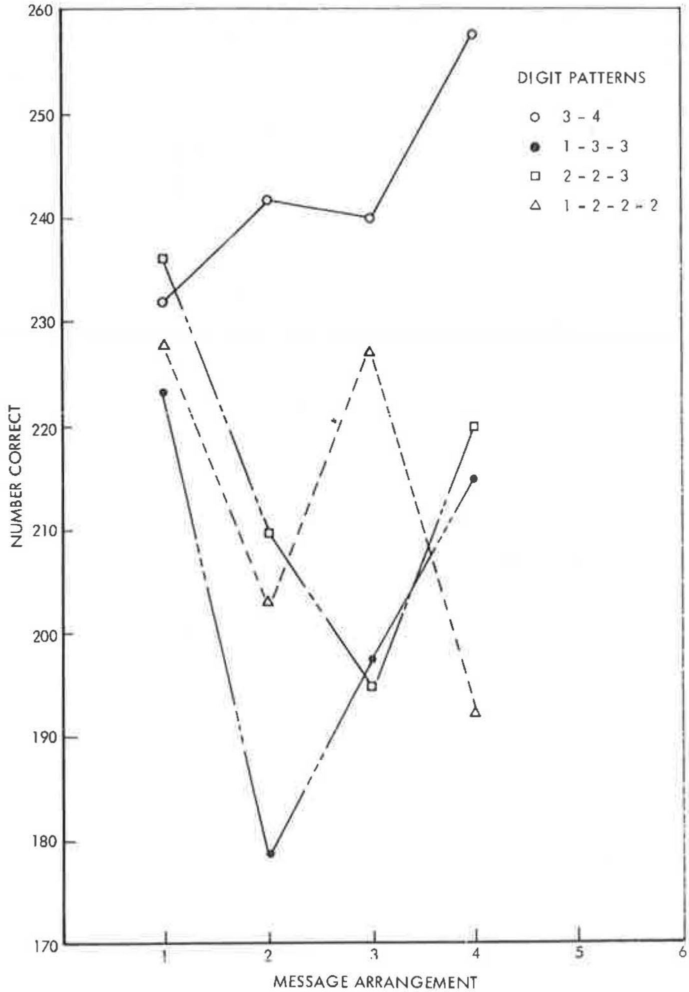

Figure 4. Effect of message format (grouping) on recall.

references (2, 3, 4, 5, 6) contain typical analyses and results of the body of data related to the parameters of code length, format, and symbolic form as these parameters influence the short-term memorization process. Figure 3 (2) shows the effect of message length and symbology upon the ability of a subject to recall a previously stated message. Figure 4 (4) illustrates results of experiments on grouping of symbols as an aid to the retentive process. The general conclusion to be reached from these data regarding preferential coding from a human factors standpoint, is that commonly recognized or used symbols, of short length, in a grouped format, would be highly desirable.

Applying these factors to the candidates (Table 1) leads one to conclude that the shorter length, higher-base symbology would be preferred from a human factors standpoint. Base 45 coding, however, contains problems in that there is no commonly used base 45 in existence today. Special symbols would have to be developed as shown on the last line of Table 1. The second from last line implements a hardware coding scheme of base 45 by doubling-up on the conventional arabic numeral digits, when necessary, at each of the four positions and uses a superscripted bar to indicate that these are special digits. The result is the equivalent of an eight-digit code requiring 180 elements, and the base 8 coding scheme in Table 1 requires only 64 elements and would therefore be more attractive.

Figure 5. Regional partitioning.

The first high-base, short code-length system in Table 1 using commonly recognized symbols is the 5-character, alphabetic-symbol base 26 system. Figure 3 indicates an alphabetic coding system is highly desirable, particularly if the code length can be held to a minimum. The question which next presents itself regards the feasibility of developing a geographic partitioning scheme which would be compatible not only with a code length of five characters, but also with the tri-level hierarchical partitioning scheme previously described.

Code Compatible Geographic Partitioning

The appellations assigned the geographic partitions derived are "region" for the most gross division of the highway network, "district" for the subdivision of the region, "sector" for subdivisions of the district, "zone" for the subdivisions of the sector, and "node" for subdivisions of the zone. Using these appellations and recalling the network hierarchy previously described, 20 intersections or nodes are grouped together to comprise a zone. These nodes are called the "minor nodes." A dominant node is chosen in the zone to be called the "secondary node." Twenty secondary nodes are grouped together to comprise a sector, so that each sector contains 20 zones. Again, a dominant node in the sector is chosen to be called the "primary node," and the 20 zones are considered to be satellites of the primary node. The primary node therefore has 400 intersections of the highway network subsequent to it. If 20 primary nodes are grouped to form a district, and 25 districts are allocated to the geographic region, then each region will have 500 primary nodes. Because of the 400-to-1 ratio of minor nodes to primary nodes, each region therefore contains 200,000 network intersections. Because it is desired to code 4 million nodes, a requirement for defining 20 geographic regions exists.

Figure 5 shows the geographic regional partitioning chosen. In order to avoid arbitrariness in boundary and area definitions for regions, the following conditions and constraints were adopted, and are reflected in Figure 5.

- Provision must be made for future expansion, hence allowance must be made for the existence of at least 10,000 primary nodes.

- The regional partitioning must provide for all existing primary nodes counted within each state. For the 48 contiguous states this amounted to 7,500 primary nodes.
- Major boundaries must follow state lines, or lie within states, but must never cross state lines. Thus, regions must lie wholly within a state or contain an integral number of states, and each state must contain an integral number of districts.
- Regions should fall into natural geographic areas for easy identification.
- Regions should contain the same number of nodes.

The conditions and constraints cited above were also reflected in the definition of districts, with the substitution of "county" for the "state" geopolitical entity. An example of district boundary determination is shown in Figure 6, district definitions

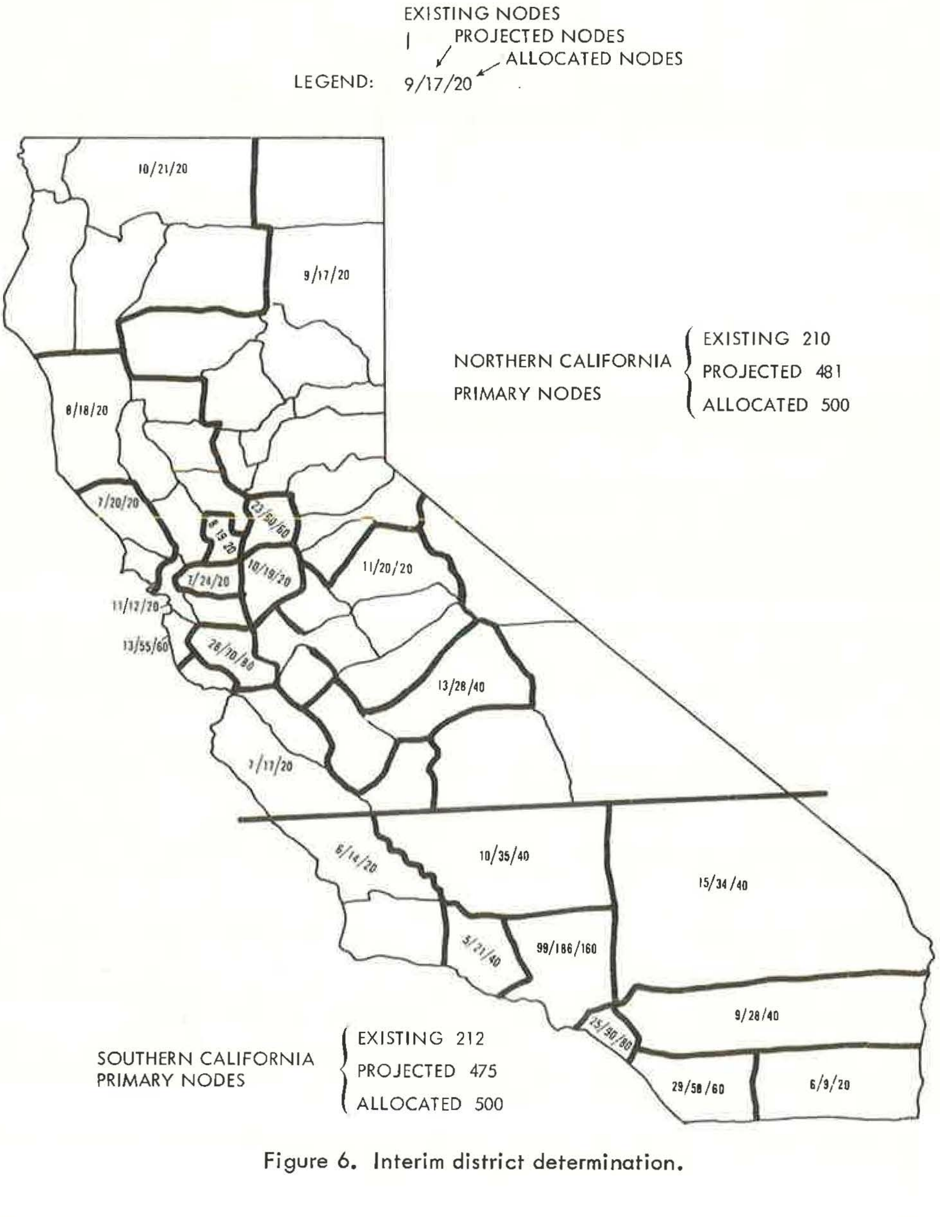

Figure 6. Interim district determination.

for California. Growth models, correlating highway network growth with population growth, were derived and applied (1) to assist in the determination of geographical partitioning boundaries. Boundary conditions for sectors and zones can be derived in a similar fashion.

Load Reduction on Communication Links

Coupling the dual geographic and hierarchic partitioning enables a reduction in information load on the system greater than two orders of magnitude. This is accomplished by recognizing that a driver's decisions in maneuvering a car through a roadway network must be made with most rapidity when the decisions concern those elements of the network closest to him. He is therefore provided with instructions regarding the finely detailed network in his immediate vicinity, which we define as the minor network in his district consisting of 8000 nodes (20 primary nodes in the district, each primary node having 20 secondary nodes, each secondary node having 20 minor nodes, and all 8000 nodes encompassed within the geographic district which is somewhat analogous in area to a county). At distances greater than his district, say in his region (equivalent somewhat in area to a state or group of states), the driver need only be furnished information about the less-detailed secondary network consisting of an additional 10,000 nodes (500 primary nodes per region, each primary node having 20 secondary nodes). For completeness, the driver need only be furnished information on a gross basis outside of his region. Thus, outside of the region in which he is receiving instructions from the roadside equipment, he is only furnished information about the primary network, which is a total of 10,000 nodes for the total contiguous United States. This hierarchic partitioning is a function of the location of the node, so that as the driver negotiates the highway network, the fine network appears to travel with him; thereby he is always furnished detailed information about the network at remote distances from him. In this way each driver is furnished optimum routing instructions for his specific destination through a network of more than 4 million nodes by only selectively referring to approximately 28,000 nodes.

Grouping destinations accessible from a given node via specific node branches enables additional reductions in roadside processing of information by the use of partial decoding of destinations common to the given node's branches. For instance, if all destinations in regions A, B, C, and D can be optimally routed out of a given node through branch 8, then an initial test on the destination's region code to see if it is the alphabetic character A, B, C, or D would suffice for optimal routing instruction transmittal to the vehicle. Further decoding of the destination's district, sector, zone, or node alphabetic characters would be superfluous and uneconomic.

Alphabetic Code Modifications

At this interim point, the coding scheme preferred is alphabetic in each of the five levels. A typical node code would be

ABCDE,

and is interpreted as the minor node E in the geographic zone of the secondary node D, which is in the geographic sector of the primary node C located in district B or region A.

Since the English alphabet can be considered a radix 26 system, almost 12 million separate nodes can be identified ($26^5 = 11.8 \times 10^6$). As only 4 million nodes need be identified, some letters may be held in reserve, and other modifications may be made to the coding scheme in order to enhance its attractiveness and acceptance by the general driving public.

One of the first modifications considered is that of state prefix coding. Region coding requires 20 alphabetic designators, so that 6 alphabetic designators can be held in reserve for growth. Since region partitioning is primarily a grouping by states, one technique which may be used is that of utilizing the common two-letter post office abbreviation for the state name included as part of the region. Thus, in the Northwest

Region of the United States, if the region designator is chosen to be A, then the constituent states of region A are Washington, Oregon, Idaho, Montana, and Wyoming, and the substituted abbreviations are WA, OR, ID, MT, and WY, respectively. If a "grouped" format is also applied to the state prefixed intersection name, then the resulting node name may appear as in the following examples:

Intersection Name		Node Code
WA-U-APE	for	AUAPE
OR-I-GON	for	AIGON
ID-A-LUU	for	AALUU
MT-M-EEK	for	AMEEK
WY-B-SAD	for	ABSAD

The mnemonic effect of the transformation illustrated is quite pronounced, and should tend to lessen reading and device input errors, and increase acceptance and confidence of the general driving public.

It has been reported that association of perceptual skills with verbalization aids the memorization process (7). This means that groups of alphabetic symbols can be recalled more readily if these groups can be made to form syllables that can be mentally verbalized. The five-level alphabetic code for 4 million nodes has the following number of divisions in each of the five levels:

Region	District	Sector	Zone	Node
20	25	20	20	20

Noting that the sector, zone, and node divisions require only 20 separate indentifiers in each, then six consonants can be eliminated from the alphabet when forming the code; resulting in a vowel-heavy alphabet and increasing the probability of forming pronounceable syllables, thus rendering the coding scheme more attractive from a human factors standpoint. Alternatively, five vowels and one consonant can be removed from each of the sector and node alphabetic designators and six consonants from the zone alphabets, so that a vowel-heavy alphabet is formed between two consonant-heavy alphabets, heightening the probability of occurrence of such syllables as DAN and BUG.

Table 2 lists the probabilities of various letter triplets occurring as a function of the type of letter (vowel or consonant) excluded from each coding level. The columns are arranged in such a way that the more easily verbalized triplets occur to the left. In row 6 the probability of triplets occurring in the code which can always be verbalized is maximized when vowels are excluded from the sector code, consonants from the zone code, and vowels from the node code. However, this selection also minimizes the percentage of triplets which can never be verbalized. On the other hand, if consonants are eliminated from all three levels (row 1), the possibility of no verbalization will be reduced by 0.33 while the reduction of the possibility of a "sure verbalization" is reduced by only 0.057, and the "sometimes verbalized" category is increased by 0.39. Therefore,

TABLE 2

OCCURRENCE PROBABILITIES

Letter Type Discarded (Sector, Zone, Intersection)	Probability of the Occurrence in the Code of (XXX*)							
	CVC	VCV	CVV	VVC	VCC	CCV	VVV	CCC
1. C - C - C	0.138	0.043	0.043	0.043	0.138	0.138	0.013	0.440
2. C - C - V	0.102	0.000	0.000	0.057	0.182	0.000	0.000	0.580
3. C - V - C	0.000	0.057	0.000	0.000	0.182	0.192	0.000	0.580
4. C - V - V	0.000	0.000	0.000	0.000	0.238	0.000	0.000	0.762
5. V - C - C	0.182	0.000	0.057	0.000	0.000	0.182	0.000	0.580
6. V - C - V	0.238	0.000	0.000	0.000	0.000	0.000	0.000	0.762
7. V - V - C	0.000	0.000	0.000	0.000	0.000	0.238	0.000	0.762
8. V - V - V	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
	Always can be verbalized		Sometimes can be verbalized					Never can be verbalized**

*X = V; Vowel
X = C; Consonant

**With the possible exception of ZZZ and SSS.

it appears that the occurrence of vowels permits more verbalization of the code, and thus, heightens the association and memorization process.

Given that the vowels are to be retained, within a coding level (i.e., sector, zone, or intersection), there are $21!/(6!\ 15!) = 54{,}264$ unique ways of removing six consonants from the alphabet. Thus, some criterion must be used to determine an appropriate set. Research aimed at measuring the association of three letter syllables has been reported (7). The six most frequently occurring consonants in syllables of low association value were observed to be H, J, Q, X, W, and Z. Consequently, when six consonants were to be eliminated from the coding, this set was chosen.

The preceding analysis has shown that hardware considerations and human factors aspects are somewhat in conflict. In order to compromise in favor of the hardware, the code should have many levels more than 5 and few elements in each level. In order to compromise in favor of human factors consideration and receive general public acceptance, a short, easily recognized and retained code is desired. The viewpoint adopted in the final selection of the code is that compromise should be made in favor of human factors and public acceptance, as long as cost penalties are not too great.

Cost Comparisons

The approach used to determine the significance of the cost differential associated with the different coding schemes is based on the following steps:

1. Estimate the equipment differences between the various coding systems, part by part, in both the vehicles and intersections.
2. Put a dollar estimate on these differences.
3. Assume a total of 70,000,000 vehicle devices costing $100 each.
4. Assume a total of 4,000,000 intersections costing $2000 each to instrument.
5. Apply the formula:

$$F_{A-B} = \frac{70 \times 10^6 (V_A - V_B) + 4 \times 10^6 (I_A - I_B)}{70 \times 10^6 \times 100 + 4 \times 10^6 \times 2000}$$

$$= \frac{70 (V_A - V_B) + (I_A - I_B)}{15{,}000}$$

where

F_{A-B} = fractional cost difference between the A and B coding systems;
V_A = vehicle system cost using coding system A;
V_B = vehicle system cost using code system B;
I_A = intersection system cost using coding system A; and
I_B = intersection system cost using coding system B.

TABLE 3

VEHICLE EQUIPMENT COMPARISON BY CODE TYPE

BASIC COMPONENT	BINARY	QUATERNARY	OCTAL	HEXADECIMAL	ALPHABETIC
	22 Inputs 1/2 Selec.	11 Inputs 1/4 Selec.	8 Inputs 1/8 Selec.	6 Inputs 1/16 Selec.	5 Inputs 1/25 Selec.
Switches	22 Toggle SWS	11-4 Pos. Dial SWS	8-8 Pos. Dial SWS	6-16 Pos. Dial SWS	5-25 Pos. Dial SWS
Cost Est.	$1.54	$3.35	$2.44	$2.82	$4.15
Sequencer	22 FF SR	22 FF SR	24 FF SR	24 FF SR	25 FF SR
Cost. Est.	$8.80	$8.80	$9.60	$9.60	$10.00
Total Cost Est.	$10.34	$12.15	$12.04	$12.42	$14.15
Cost Difference Compared to 5 inputs, 1/25 Sel.	-$3.81	-$2.00	-$2.11	-$1.73	0

Abbreviations: FF Flip-Flop
SR Shift Register
SWS Switches

TABLE 4

INTERSECTION EQUIPMENT COMPARISON BY CODE TYPE

BASIC	BINARY	QUATERNARY	OCTAL	HEXADECIMAL	ALPHABETIC
COMPONENT	22 Inputs 1/2 Selec.	11 Inputs 1/4 Selec.	8 Inputs 1/8 Selec.	6 Inputs 1/16 Selec.	5 Inputs 1/25 Selec.
Destination Register	22 FF SR	22 FF SR	24 FF SR	24 FF SR	25 FF SR
Costs	\$8.80	\$8.80	\$9.60	\$9.60	\$10.00
Sequencing Costs	22 6-Input Gates	22 6-Input Gates	24 6-Input Gates	24 6-Input Gates	25 6-Input Gates
Costs	\$12.10	\$12.10	\$13.20	\$13.20	\$13.75
Storage Unit	13,500 Serial Mem. Bits	13,500 Serial Mem. Bits	14,500 Serial Mem. Bits	14,500 Serial Mem. Bits	15,000 Serial Mem. Bits
Costs	\$270.00	\$270.00	\$290.00	\$290.00	\$300.00
Total Costs	\$290.90	\$290.90	\$312.80	\$312.80	\$323.75
Cost Difference Compared to 5 Inputs, 1/25 Sel.	-\$32.85	-\$32.85	-\$10.95	-\$10.95	0

Abbreviations: FF Flip-Flop
SR Shift Register

The estimates of 70 million vehicles at \$100 each and 4 million intersections at \$2000 each are based upon conjecture of eventual mass production of these items in a configuration which provides for the route guidance function only.

The cost comparison for the vehicle equipment is given in Table 3. Only the switches and sequencer costs are significantly affected by the coding choice. The cost difference line, at the bottom of the chart, is the $(F_A - V_B)$ value, where B designates the five-level, 1/25 (one out of twenty-five elements) selection coding system used as a reference.

The cost comparison for the intersection equipment is given in Table 4. The destination register, sequencing gates, and storage unit costs are significantly affected by the coding choice. The cost difference line (at the bottom of Table 4) is the $(I_A - I_B)$ value, where B designates the five-level, 1/25 coding system used as a reference.

Referring to the F_{A-B} formula and the bottom lines of Tables 3 and 4, the fractional cost comparisons are evaluated below, all with reference to the five-level, 1/25 selection coding system:

<u>Twenty-two input ½ selection</u>

$$(V_A - V_B) = -\$\ 3.81$$

$$(I_A - I_B) = -\$32.85$$

$$F_{A-B} = \frac{70\ (-3.81) + 4\ (-32.85)}{15{,}000} = -\ 0.0265$$

$$= -\ 2.65\%$$

Thus, the use of 22 toggle switches instead of five 25-position rotary switches results in a 2.65 percent overall cost saving. It may be noted that 1.21 percent of this saving is due to the low cost of small SPDT toggle switches (estimated at 7 cents per piece in large quantities) and 0.87 percent is due to the savings in memory.

<u>Eleven input, ¼ selection</u>

$$(V_A - V_B) = -\$2.00; \quad (I_A - I_B) = \$32.85$$

$$F_{A-B} = \frac{70\ (-2.00) + 4\ (-32.85)}{15{,}000} = -\ 0.181 = -\ 1.81\%$$

The memory savings here is also 0.87 percent.

STATE: Washington			
City or County	Intersection	Node Name	Code Name
Tacoma	I 5 - RT7	WA-G-FAB	AGFAB

Figure 7. Intersection directory format, driver oriented.

Eight input, 1/8 selection

$$(V_A - V_B) = -\$2.11; \; (I_A - I_B) = -\$10.95$$

$$F_{A-B} = \frac{70\,(-2.11) + 4\,(-10.95)}{15{,}000} = -0.0127 = -1.27\%$$

Sixteen input, 1/16 selection

$$(V_A - V_B) = -\$1.73; \; (I_A - I_B) = -\$10.95$$

$$F_{A-B} = \frac{70\,(-1.73) + 4\,(-10.95)}{15{,}000} = 0.0110 = -1.10\%$$

On the basis of this cost comparison, the conclusion can be reached that on a total program basis, no coding system is capable of implementation in the foreseeable future that will realize cost savings of more than 2.65 percent over the alphabetic coding system. This additional cost is a small price to pay for convenience and higher probability of acceptance by the general public. Consequently, the coding system chosen is a five-level, alphabetical-digit code, with the region designator (the left-most letter) of the code replaced by a two-letter state abbreviation for general public use.

Intersection Directory

Assuming that the route guidance system is implemented, the problem of informing the general public of the node code presents itself. To assist resolving this problem, an intersection directory is proposed. An intersection directory of the primary nodes of the contiguous United States has been published (1). Two formats are used.

The first format is driver oriented, and assists a driver to determine the intersection (node) code closest to his destination. To use this directory, a standard road map is consulted to determine the intersection closest to the driver's destination. The route designators are then noted for this node, such as Interstate 5 (I5) and State Highway 7 (RT7). The directory is then consulted on a geographical basis by first going to the appropriate state, city or county division of the directory, and then looking up the route designators (I5-RT7) noted from the map. The directory then provides the proper node name to be input. Figure 7 illustrates this directory format.

STATE: Washington			
Code Name	Node Name	City or County	Intersection
AGFAB	WA-G-FAB	Tacoma	I 5 - RT7

Figure 8. Intersection directory cross-reference format.

The second format (Fig. 8) is oriented more toward supporting the administrative functions of a highway. Here the listing in the directory is alphabetic by the five-letter code, which is the first column listed in the directory. The next column cross-references the state abbreviation prefixed code, the next column stipulates the city or county in which the node is found, and the final column gives the route markers of the roads forming the intersection.

Node Record and Data Files

All the items of information concerning an intersection (code, location, node branches, next sequential node, and branch distance measure) constitute data items which form a necessary record for the proper functioning of the route guidance concept. To this necessary record may be appended data items considered ancillary or even unrelated to the route guidance function, but of interest to the local agency maintaining files of records on highway network status. This attachment would include such data items as highway geometrics, construction details, construction costs, traffic count statistics, maintenance data, and accident and related safety statistics. Although not exhaustive, the preceding list serves to illustrate that route guidance data records could serve as a framework for construction of highway data files for local agency use.

In order to assist in the data recording function for route guidance, a format was chosen for record-keeping (Table 5). A maximum of three 80-column computer cards is allocated for entering the route guidance data for each node. If other data are desired, the data may be appended with the use of additional cards, the node code serving as the "key," for subsequent retrieval, manipulation, and processing. Using the format of Table 5, sorting of network data can be accomplished geographically (by region,

TABLE 5

CARD RECORD FORMAT

CARD #1

Column Number	Field Entry	Remarks
1	Blank	
2-6	5-level Alpha Node Name	
7	Blank	
8-9	Alpha State Code	Following U.S. Mail Standard Abbreviations
10	Blank	
11-13	County Code	
14	Blank	
15-29	City Code and/or Township-Range Location Code	Decided by City or County Officials
30	Blank	
31	Branch Designator	1-8 by Compass Octants
32	Blank	
33-43	Old Route Designator	Highway Number, Street Name, County Highway Number. Also Distance Measure could be entered.
44	Blank	
45-49	Name of next node on this branch.	
50-69	Repeat on 30-49	
70	Blank	
71	Blank or *	*After last branch to stop reader
72	Blank	
73-80	Numbering of data decks	May be numbered as desired for sorting.

CARD #2 AND CARD #3

Column Number	Field Entry	Remarks
1	X	For sorting purposes. Also reader knows of different format to follow.
2-6	Node Name	Same entry as 2-6 on Card #1
7	Blank	
8-9	Alpha. State Code	
10-29	Same as 30-49 on Card #1	
30-49	Same as 10-29	
50-69	Same as 10-29	
70	Blank	
71	Blank or *	
72	Blank	
31, 51, or 71 or not at all	*	*After last branch To stop reader. Comments may follow.

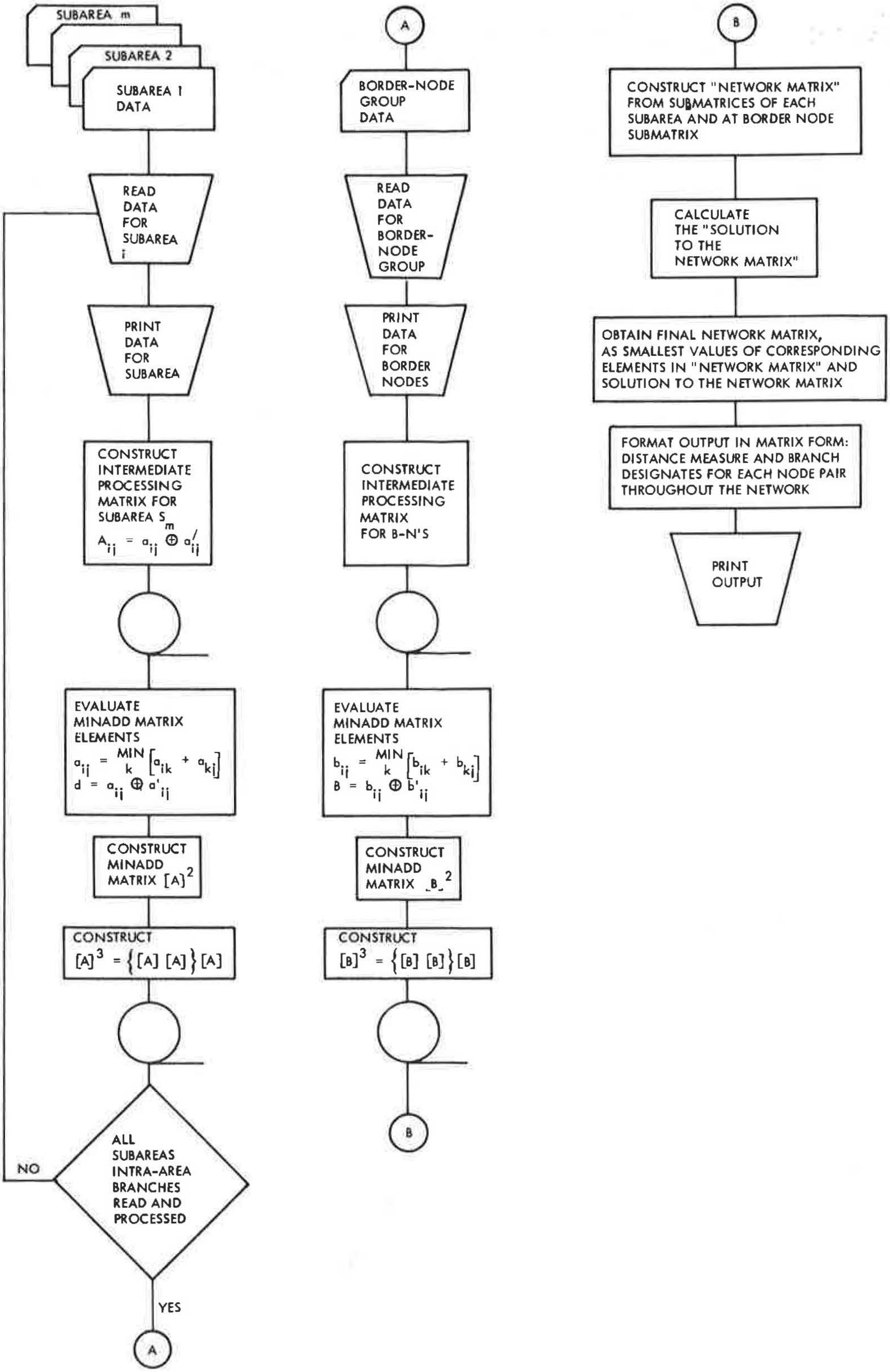

Figure 9. Shortest route program flow chart.

district, sector, zone, and node), heirarchically (by primary, secondary, and minor node), by state, by county, by city, branch designator, branch distance, route, or next node name. This type of sorting permits route following to be accomplished so that all the nodes on any given route in the network can be listed.

OPTIMAL ROUTES DETERMINATION

In anticipation of solving a convenient network of highway routes over a prototype model of the information exchange equipment, a FORTRAN IV program for solution of optimal routes has been written and compiled on Philco Model 212 computers. The flow chart for this program is shown as Figure 9.

This program determines the shortest route distance and the branch which yields this route between each pair of nodes in a matrix representation of the network. Partitioning a large network allows a considerable reduction in computation steps and processing time by decomposing the matrix into several proportionately smaller arrays, and solving each separately. The shortest routes of each subnetwork are then interstitched using the concept of "border-nodes" for each subarea. It has been found that the number of iterations of the border-node search procedure plus those for the complete search within each subarea are fewer than would be required if all of the nodes of the total network are searched without partitioning.

The computer program uses a process called minaddition first described by Shimbel (8). In ordinary matrix multiplication, the product of two matrices a and b defined as

$$a = a_1, a_2, \ldots, a_n$$

$$b = b_1, b_2, \ldots, b_n$$

is

$$a \cdot b = a_1 b_1 + a_2 b_2 + \ldots, a_n b_n$$

Minaddition of a and b is defined as

$$\text{Minaddition } (a, b) = \min_k (a_k + b_k)$$

i.e., the minimum of all sums $a_k + b_k$ taken over all k.

If the rules of matrix multiplication (and squaring) are retained except when minaddition is substituted in the formation of the product matrix, then the type of multiplication used in the computer program for determining optimal routes is defined.

Shimbel has shown that if the original network matrix is successively squared, at most r times, the resultant matrix is the solution to the original network matrix. The maximum number of times r that the matrix must be squared is given by

$$2^r \geqq n > 2^{r-1}$$

where n is the number of nodes in the network, i.e., the matrix is an nxn matrix.

Use of the Shimbel minaddition process plus the partitioning technique previously described permits the FORTRAN IV program developed at Philco-Ford to solve for optimal routes in network matrices of up to 1564 nodes with a computer run time of approximately 2 hours.

SUMMARY

A system for uniquely coding and formatting over 4 million nodes (intersections) of the contiguous United States roadway network has been devised, and a computer program for the determination of optimal routes over an instrumented network of up to 1,500 nodes has been written and tested. The code is alphabetic, short, and vowel-heavy, with notable mnemonic effects. A dual form of partitioning is used in coding the roadway network, thereby lessening the information load on the communication

link between the roadway and the vehicle. Over 7000 major intersections of the U.S. Highway network have been coded in a machine language format based on the node code as a key, and an intersection directory has been compiled and published through use of the machine language and node code.

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A Design for an Experimental Route Guidance System

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This paper describes an experimental route guidance system (ERGS) designed by General Motors Corporation under contract (No. FH-11-6626) to the Federal Highway Administration, Bureau of Public Roads.

The objective of the design was to develop an electronic system which would automatically provide drivers with routing instructions at decision points in the road network along the way to their respective destinations. System hardware consists of both mobile and fixed elements, which automatically establish two-way digital communication between moving vehicles and antennas embedded in the roadway.

The system is destination oriented. At the beginning of his trip, the driver enters a code word representing the address of his destination into the unit in his car. As his vehicle approaches each instrumented intersection, the destination code is transmitted to the roadside equipment, where it is decoded in accordance with a stored program. An appropriate maneuver instruction is calculated, returned to the vehicle, and displayed to the driver in the length of time necessary for the vehicle to travel a distance of approximately five feet at Interstate Highway driving speeds.

•THE system design described in this paper was developed by General Motors Research Laboratories and Delco Radio Division, General Motors Corporation, under contract (No. FH-11-6626) to the Federal Highway Administration, Bureau of Public Roads (1). The paper describes a hardware system design to implement an experimental route guidance system (ERGS).

The primary objective of ERGS is to automatically provide drivers with routing instructions at decision points in the road network. These instructions successively guide the vehicle along the "best route" to its destination.

The system design requires the installation of electronic equipment in each vehicle which is to receive routing instructions and the installation of roadside equipment at each intersection which is to supply routing instructions. This road and vehicle equipment (Figs. 1 and 2) establishes a two-way digital communication link between every equipped vehicle in the traffic stream and the roadside. It also provides the logic systems needed to process the road-vehicle digital communications.

The ERGS system is destination oriented and makes use of a coding system which is designed to uniquely identify all intersections in the continental United States (2). A driver may address any intersection in the country as a destination by entering the assigned code word for this specific destination into the vehicle equipment. Then, as his vehicle approaches each instrumented intersection, this code word is communicated on command to the roadside equipment which determines how the vehicle should leave the intersection to best reach its destination, encodes the appropriate routing maneuver instruction and then communicates it back to the vehicle.

Paper sponsored by Special Committee on Electronic Research in the Highway Field and Committee on Traffic Control Devices and presented at the 48th Annual Meeting.

Figure 1. Vehicle Equipment—the communication antenna (not shown) is located under the rear of the vehicle.

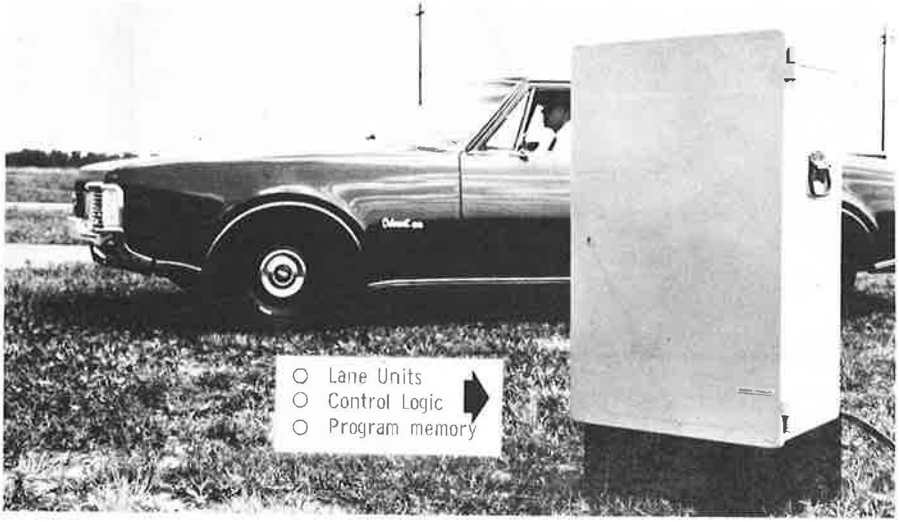

Figure 2. Roadside Equipment—the communication antennas (not shown) are deployed in each inbound traffic lane of the intersection.

The best-route instructions which the driver receives are derived from a stored program in the roadside equipment. The program for each intersection equipment is generated according to a best-route criterion, such as minimum trip time, from road network data and then written in the roadside memory unit by means of punched tape.

The destination-oriented approach to route guidance offers the driver two distinct advantages over a route-oriented system. First, the driver is independent of any route programming source. The only information he requires is knowledge of the code word for his specific destination. This does not mean that the driver is without control over the route he will take. He may program his own route by successively addressing intermediate destinations which lie on the route he wishes to take to his final destination. The ERGS roadside equipment will instruct him on best routes to these intermediate destinations. The second advantage of the destination-oriented approach to route guidance is that the driver cannot get lost in the network. If, for any reason,

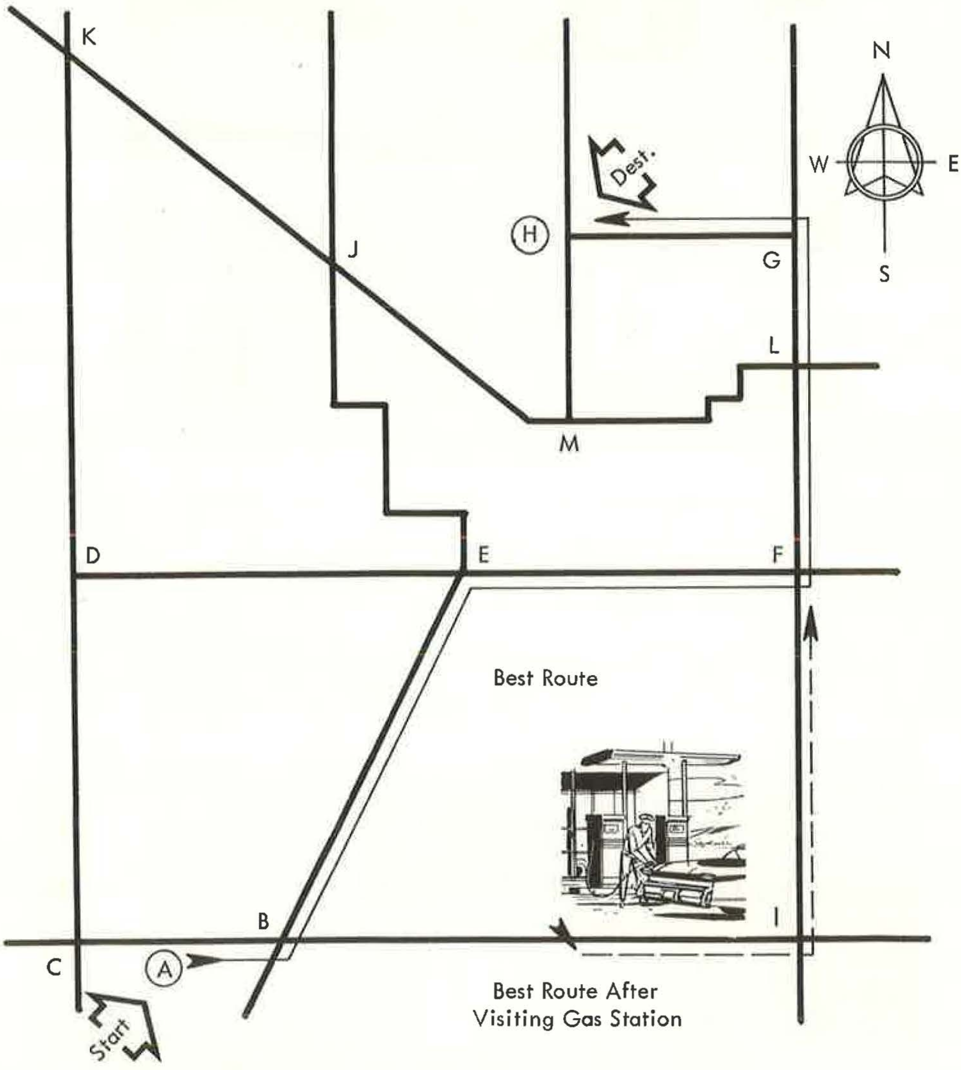

Figure 3. Instrumented Road Network—the paths show the routes of vehicles bound for intersection H from two origins in the network. Routing instructions are received in the vehicle as it approaches each instrumented intersection.

he does not follow the instruction at an intersection, the next instrumented intersection he approaches will direct him to his specified destination from that point.

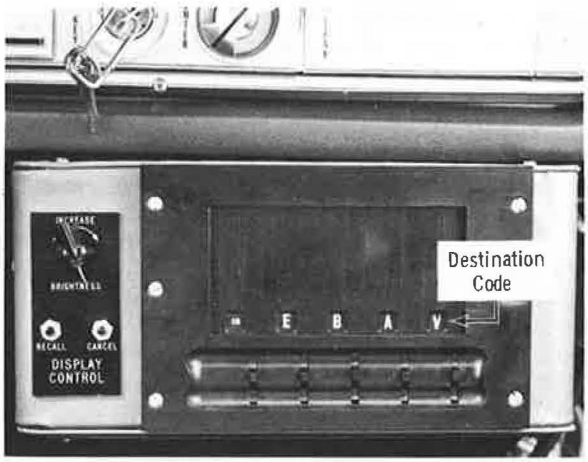

Figure 4. Destination Encoder—the driver enters the code word for his destination at the start of each trip.

To describe the overall operation of the system, let us follow an equipped vehicle on a short trip through the instrumented network shown in Figure 3.

Assume that the vehicle starts from point A, and its destination is node H. Before starting the trip, the driver consults a destination code source (which could resemble a postal zip-code book), from which he obtains the route guidance code word for node H. Alternatively, if he intended to stop at a motel or other commercial establishment located at node H, he might obtain the destination code from their literature or advertisement. To inform the route guidance system of his desired destination, he enters the code word into the encoder on the front panel of his vehicular unit by turning the five thumbwheel coding switches until the desired code word appears in the encoder windows (Fig. 4). Thus set, the destination code word remains in view throughout the entire trip, providing visual verification of the preset destination.

Upon entering the highway system at point A, the driver must proceed to the first instrumented node before receiving the first routing instruction. Let us assume that he knows his destination lies generally northeast of his starting point, and accordingly starts east toward node B. As he approaches node B, he crosses a road antenna embedded in the surface of the pavement, initiating the following sequence, which transpires in less than the time required for the car to cross the antenna.

1. His vehicular unit receives a trigger signal from the road antenna, causing it to transmit the preset destination code word to the road antenna.
2. The destination code is received and processed by the roadside decoder, and an appropriate instruction message is returned to the vehicle.
3. Within the vehicle, the received instruction is visually presented on a driver display panel (Fig. 5) until either extinguished at the end of a preset time period or replaced with a fresh message at the next instrumented node.
4. Display of the routing instruction is accomplished by a momentary audible tone to inform the driver that an instruction has been received.

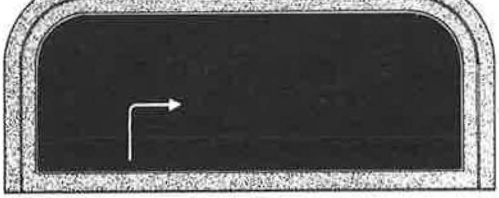

Figure 5. Driver Instruction Display—the display shows the symbol used to instruct the driver to make a simple right-turn maneuver.

In this example, a symbol indicating TURN LEFT will be presented to the driver at node B. As he continues his trip, following each instruction presented to him, he will subsequently receive a TURN RIGHT instruction at node E, TURN LEFT at F, STRAIGHT THROUGH at L, and TURN LEFT at G, and END at H, his destination.

Since ERGS is a destination-oriented guidance system, each instrumented node will direct him from the point toward his destination, regardless of the path he has followed in arriving there. From this, it follows that a driver within a fully deployed portion of an ERGS network cannot lose his way for more than a short period of time even if he ignores or fails to follow a routing instruction. For example, returning to Figure 3 and assuming the driver is again starting from point A with node H as his destination, let us examine the response of the route guidance system if upon arriving at node B and receiving a TURN LEFT instruction, he had chosen instead to go to the gas station which he saw east of node B. After leaving the gas station and returning to node B, he then appeared to the node B roadside unit as a westbound driver requesting the route to node H, and accordingly, received this time a TURN RIGHT message. Had he instead continued east to node I after leaving the gas station, the best route from that point to node H would have been via link I-F, and the ERGS unit at node I would have presented a TURN LEFT instruction, followed by STRAIGHT THROUGH at node F.

Thus, each time he approaches a node, an independent, new routing message, based on his present position in the road network, is selected for him. Although the ERGS unit in his vehicle remembers his destination throughout the entire trip, each individual roadside decoder retains this destination code only long enough to process it and return an appropriate routing instruction to the vehicle.

DIGITAL COMMUNICATIONS LINK

The communication link is critical to successful operation of the ERGS system and required the consideration of several major factors before details of the design were undertaken.

An important requirement for the ERGS communication link was that it conform to Federal Communications Commission regulations. Any system which interferes with existing communications or requires reallocation of a large segment of the frequency spectrum would not likely be considered in the public interest. Therefore, in the ERGS design careful attention was given to bandwidth and frequency requirements.

Economic considerations also affect the design of the communications system. The ratio of automobiles to intersections (estimated at 20/1) dictates that system complexity be transferred from vehicular equipment to roadside equipment in order to minimize total system costs.

Communication errors would rapidly destroy user confidence and consequently could limit effective utilization of ERGS; therefore, system reliability is essential. This affects the communication link in two ways: first, the vehicle portion of the communication equipment should be as simple and reliable as possible, since maintenance of this equipment is the vehicle owner's responsibility and servicemen capable of repairing complex equipment may not be readily available to him; second, the communication link should provide a high degree of immunity to interference from other ERGS transmitters, lightning, automotive ignition systems, and other sources of noise.

The choice of two-way rather than one-way communication of information between road and vehicle was an easy decision to make. The marked reduction in transmitted data made possible by two-way communication sharply decreases the time-bandwidth requirement of the communication link and eliminates the need for the decoding of information in the vehicle.

In addition, one-way communication, from the road to the vehicle, would preclude the possibility of the road system receiving useful information from the vehicle, e.g., the vehicle's destination, its classification and its identification. Information such as this may be important in the future to urban traffic control and urban transportation planning.

The reduction in the information handling problem made possible by the decision to use two-way road-vehicle communications, made practical the consideration of a low frequency (30-300 KHz) near-field link or a narrow bandwidth far-field link.

If a far-field system were employed, many frequencies would have to be used to avoid transmitter interference problems between adjacent ERGS units. These extra frequencies would not only add to the bandwidth requirements and drastically increase the vehicle receiver cost, but also introduce the problem of setting the vehicular receiver to the required frequency channel.

The channel selection problem and the problem of obtaining a frequency allocation for routing purposes were greatly reduced by using a near-field link in which the transmitting and receiving antennas are in such close proximity that the effective field is confined to a single vehicle.

Furthermore, near-field RF meets the system requirement that the communication link selectively address each car which requests a routing instruction, in order to return the proper instruction to the car which requested it.

Finally, due to the proximity of the transmitter and receiver in such a system, the number and severity of external noise problems are greatly reduced. For these reasons, the near-field radios should have substantially reduced complexity, lower cost, and better reliability than their far-field counterparts.

The elements of the communications link are identified in a system block diagram (Fig. 6). The system design requires deployment of a road antenna in each inbound traffic lane of the intersection. When antennas must be placed in adjacent lanes, they are staggered longitudinally to provide a minimum of seven feet separation. This constraint is imposed to eliminate interfering cross-talk between adjacent road antennas,

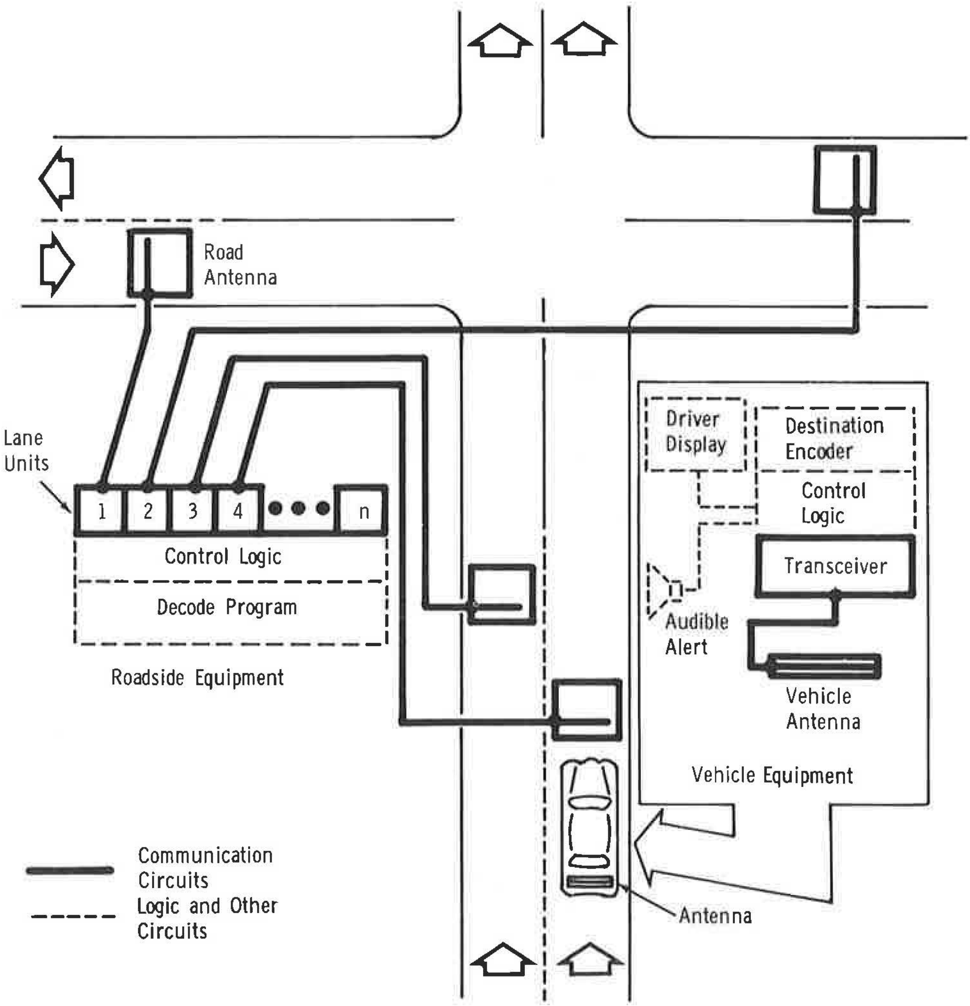

Figure 6. Block diagram of ERGS road and vehicle equipment, showing deployment of equipment at an intersection.

which might otherwise introduce communication errors. Each road antenna is connected to its own terminal equipment (lane unit). Each lane unit is serviced by one processing logic which is common to all lane units at that intersection.

Communication of information from the vehicle to the road is not initiated until the vehicle antenna is inside of the area bounded by the road antenna. Processing of the vehicle destination code and return of the routing instruction to the vehicle is completed before the vehicle leaves this area. The road antennas, communication rate and central data processing rate are designed to handle up to 16 lanes of 75-mph traffic under worst case load; that is, 16 vehicles simultaneously requesting routing information.

The only constraint placed on the traffic stream is that vehicles must be within the lane boundary to receive routing instructions; no provision is made in the present system design to communicate with straddle-lane vehicles.

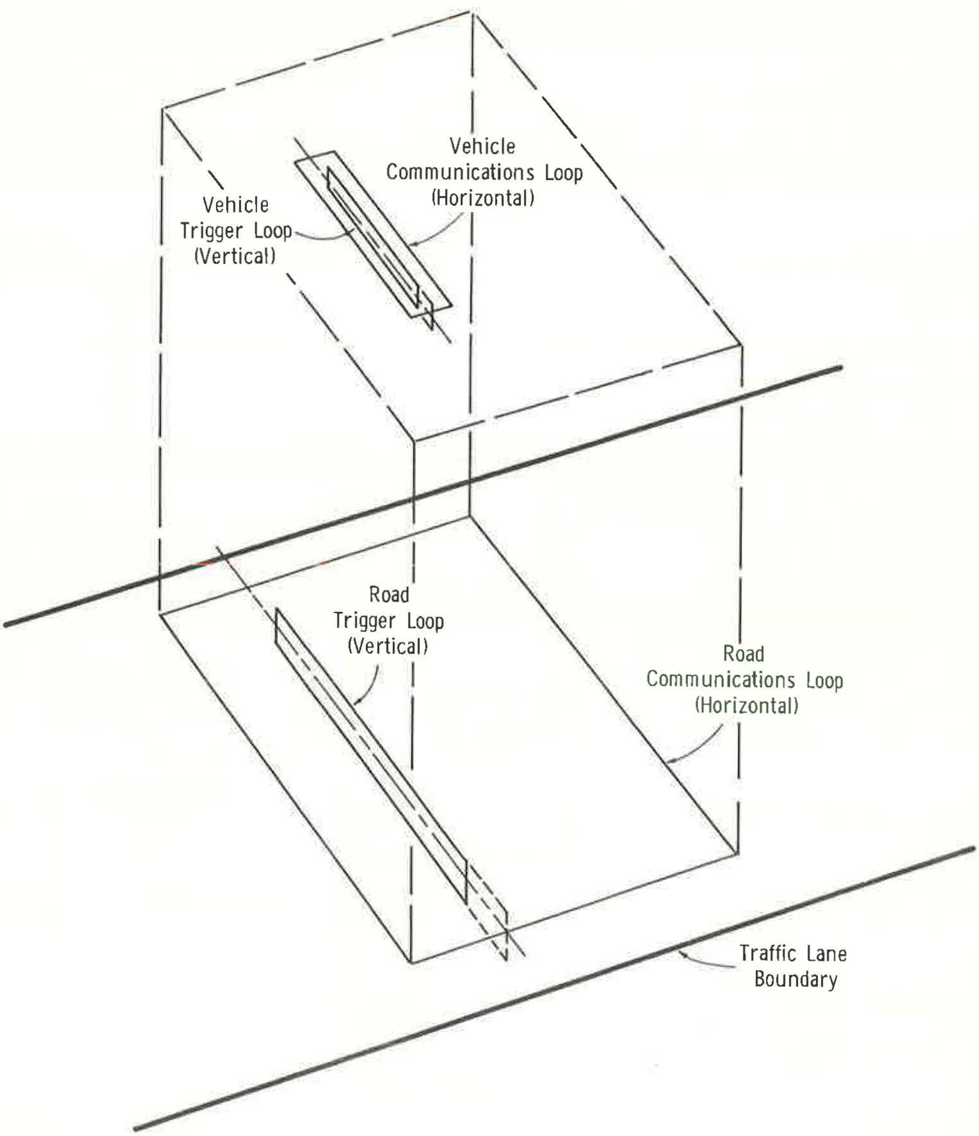

Figure 7. Roadway and vehicle antenna system, showing the geometrical relationship of the antenna loops during communication.

The road and vehicle antennas are electrically and mechanically similar. Each consists of two loops set in quadrature with respect to each other (Fig. 7). The larger road and vehicular antennas are located in horizontal planes. When the vehicle antenna is located over the road loop, these planes are separated by about 14 inches and provide for the communication of information between the road and vehicle through mutual coupling of magnetic fields. During the transmission of the vehicle destination code to the lane unit, the vehicular antenna is electrically energized and produces a magnetic field which induces a voltage in the road antenna. During the transmission of the driver instruction code, from the road to the vehicle, the road antenna is driven and a voltage is induced in the vehicular antenna.

The smaller, vertically oriented road and vehicular antennas are used to provide the trigger function which initiates transmission of the vehicle destination code to the roadside. To perform this function, the road trigger loop is the driven element and the voltage induced in the vehicular trigger loop initiates transmission of data.

The trigger antennas are only one inch high in the vertical plane and are linked by the horizontal component of field. Both road and vehicle antennas are tuned to parallel resonance at their loop terminals.

The road loops are installed by cutting slots in the pavement and 2-in. diameter holes at the loop terminals to accommodate the tuning capacitors. Additional slots are cut in the pavement to run the feedlines back to the lane units.

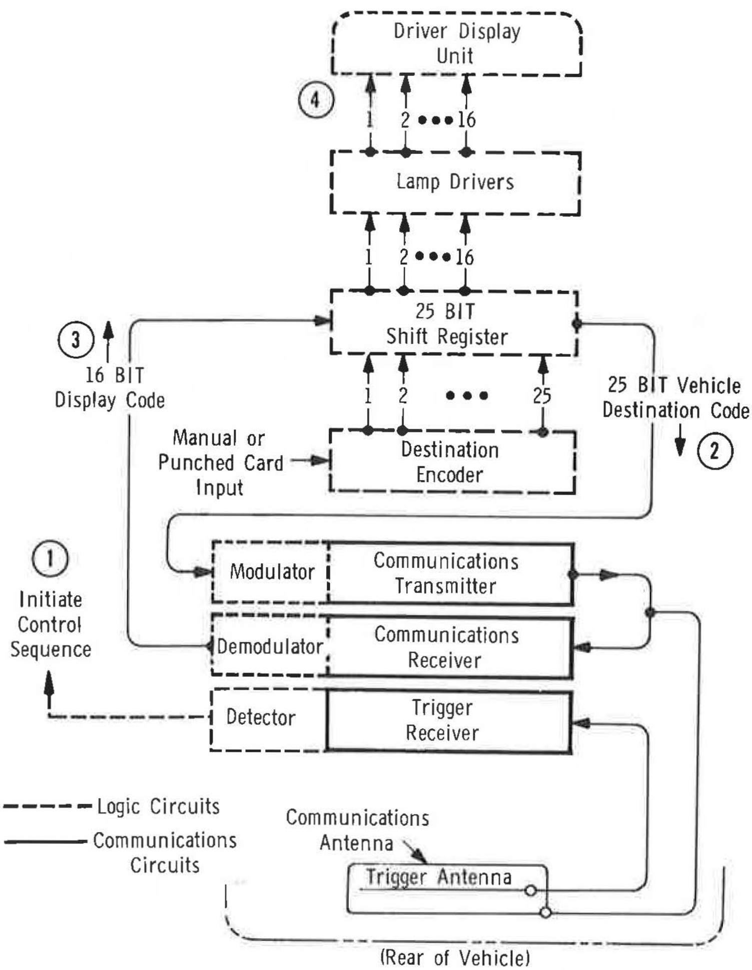

Figure 8. Block diagram of vehicular equipment, showing the flow of information in the vehicular unit.

The operation of the vehicle and road communication link is explained with the aid of Figures 8 and 9. The road trigger transmitter supplies a continuous 230 KHz carrier to the trigger antenna. When this field is intercepted by the vehicle antenna and detected by the vehicle trigger receiver, a command to transmit the vehicle destination code is generated. The destination code is stored as 25 bits of binary data in the vehicle shift register. The transmit command causes the vehicle communication transmitter to be modulated by the destination code stored in the register, serially transmitting the data to the lane-unit antenna where it is detected and stored in the lane-unit register. The communication transmitter operates on a carrier frequency of 170 KHz with a digital modulation rate of 2 kbps.

After the destination code has been stored in the lane-unit buffer it is processed by the central logic which selects from its memory the appropriate driver instruction display code. The display code is then stored in the lane-unit register in the form of 16 bits of binary data which are then serially transmitted back to the vehicle by the lane-unit communication transmitter. The display code is received by the vehicle communication receiver and stored in the vehicle register. After the 16 data bits have been stored they are used to energize the appropriate display elements thereby presenting

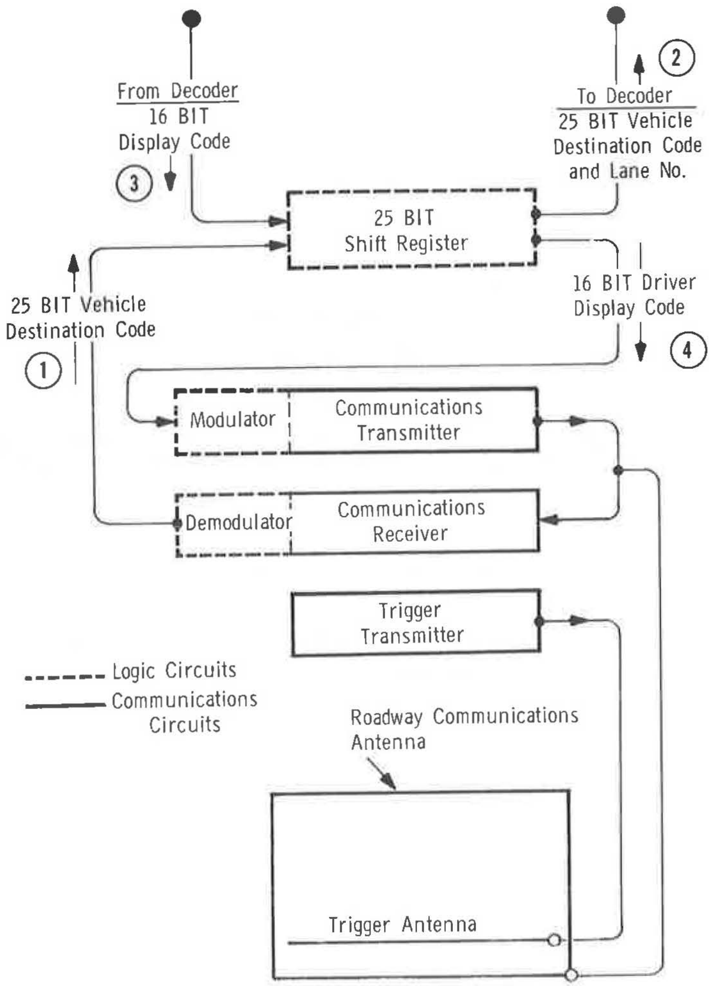

Figure 9. Block diagram of lane equipment, showing the flow of information in the roadside lane unit.

the routing maneuver to the driver. The entire process requires between 21 and 24.5 ms, depending on the lane unit loading of the central processor.

ROADSIDE LOGIC

The flow of information in the roadside central processor is shown in Figure 10. All lane-unit registers are serviced by a lane-unit register control. This control sequentially scans each lane-unit register until it detects a register loaded with a vehicle destination code. The control then stops scanning and transfers the code into the destination decoder, where it is decoded character-by-character according to the stored decode program. The decoding process is completed when an exit-path number is obtained.

In the simplest case an exit-path number specifies the branch road by which the vehicle is to leave the intersection. This is the case when the branch road has only one outbound traffic lane. In the general case, there are as many exit-path numbers as there are different ways for vehicles to leave the intersection. Figure 11 shows an intersection with an assignment of 12 exit-path numbers, whereas, there are only 4 exit branches.

The concept of exit paths is important if drivers are to receive high-quality routing instructions. For example, exit-path 4 or 6 would be specified for vehicles required to make a left or right turn at the next intersection (A). They make it possible to assign vehicles to particular exit lanes in preparation for their next maneuver. Without this ability, a driver may find himself in a traffic lane from which he cannot safely or legally be given the best routing to his destination.

Along with the exit-path number, the inbound lane-identification number is supplied to the driver instruction selector. Sufficient information (inbound and outbound states) is now available to select the appropriate maneuvering instruction (instruction number). The selected instruction number is then encoded in the form of a 16-bit display code for transmission back to the vehicle.

Each bit of the display code controls one element in the driver display unit. This method of coding makes it unnecessary to provide display decoding circuits in the cost sensitive vehicle equipment.

Destination decoding, instruction selection and encoding are all programmed into the roadside equipment. The data are stored in a 1024 word, 8 bits per word core memory.

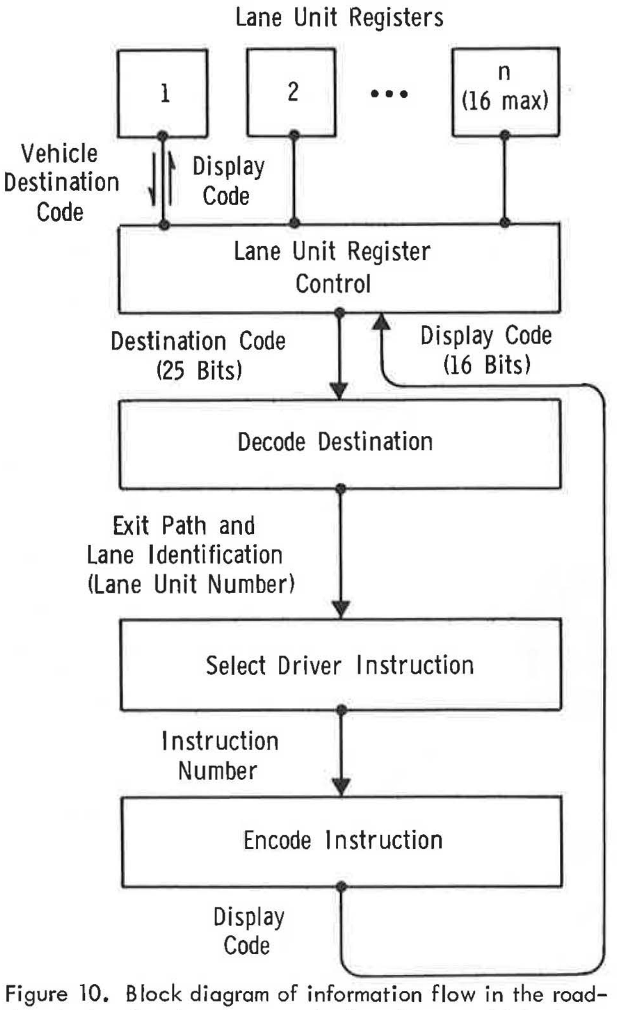

Figure 10. Block diagram of information flow in the roadside logic, showing the steps in decoding a vehicle destination code and the selection of a maneuvering instruction (display code) to be returned to the vehicle.

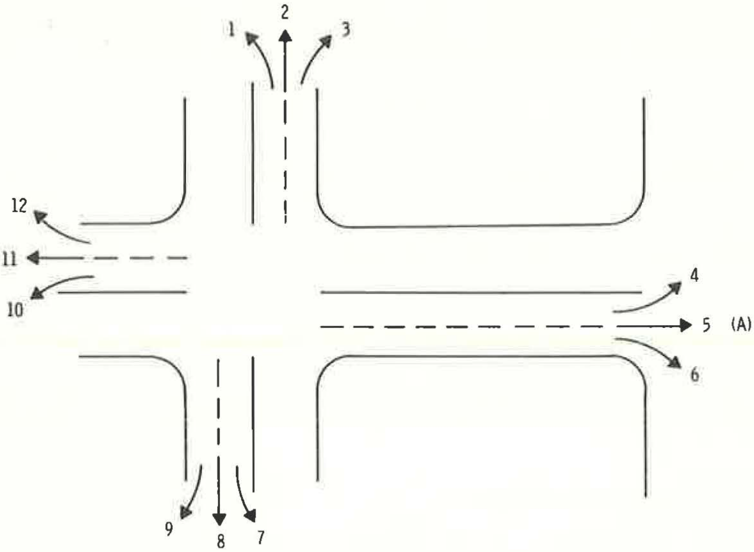

Figure 11. Assignment of exit-path numbers to an intersection; exit-path numbers permit vehicles to be assigned to particular lanes of outbound branch roads.

Provisions have been made in the program logic to insure compatibility with time variant intersection traffic control, such as no-left-turn constraints during morning and evening peak loads. This is accomplished by selecting a programmed alternate instruction number when the traffic constraint is in effect. The result is a legally acceptable maneuver but one which may no longer provide the driver with a best route to his destination. To insure drivers best routes under time variant traffic control conditions would require altering part or all of the destination decode program stored in the roadside unit. This would be the first step in the direction toward a dynamic route guidance program.

Although the ERGS system design is intended to be a static routing system, the decoder design is expandable to dynamic operation in which a central computer, operating in real time, updates the program stored in the memory of each roadside unit as necessary to reflect changes in best routes under varying conditions of traffic loading. The decoder is designed to time-share the program loading operation in between communication with vehicles; therefore, the stored program may be altered without interruption of service. This could be accomplished, for example, by means of a wired Dataphone link from a central information processing facility.

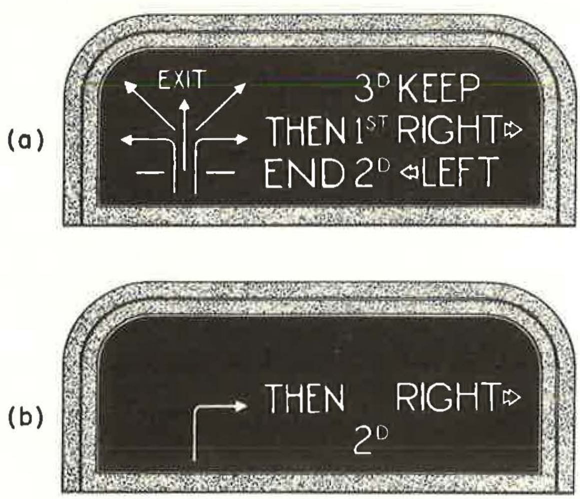

Figure 12. Driver instruction display, consisting of 16 back-lighted elements (a). Instructions are formed by lighting combinations of these elements (b).

DRIVER DISPLAY

The driver display, designed as part of this equipment, is a trans-illuminated unit which presents routing instructions in the form of sixteen graphic and verbal symbols (Fig. 12). The graphic symbols are presented when the required maneuver is simple and no ambiguity is encountered in its use. For more complex instructions the verbal symbols and combinations of graphic and verbal symbols may be used (Fig. 12 b).

The display is capable of generating approximately 100 different maneuvering instructions that are useful in guiding drivers through the maze of intersections found in the present road network.

ACKNOWLEDGMENTS

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Experimental Route Guidance Head-Up Display Research

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The head-up display is a new technique developed by the aerospace industry as a pilot landing aid. This concept provides a virtual image symbolic representation of the visual scene projected on the windshield of the aircraft and superimposed on the real world. The symbology is focused at infinity and permits the pilot to observe both the real world, the superimposed image and other visual cues without lowering his head to look at the instrument panel. The term "head-up display" was coined to describe this feature. This technique has been adapted to present directional symbols to the driver in the same manner so that he need not take his eyes off the road. The design of the vehicle display unit is derived from evaluation and tradeoff of the various optical and electronic techniques developed for an aircraft application. Design criteria were established to meet the objectives of optimum image quality, minimum package size, and most economical cost. Several alternative approaches to display design were investigated that involved various types of lenses, reflecting surfaces, and symbol production techniques. Other engineering considerations involved included temperature and vibration environment, vehicle design, and safety. A feasibility model of the selected approach was built and delivered to the Bureau of Public Roads for road testing in their experimental vehicle and subsequent incorporation in the route guidance test network.

•FUTURE urban and highway planning must consider the requirement for providing a system for coordinating urban traffic control and en route highway guidance that will enable traffic flow to be regulated in an orderly, efficient and safe manner. Many more miles are being added to the Interstate Highway System each year. New freeways are being constructed between and around urban areas. The complexity of these modern road systems, with their multi-level interchanges and multiple intersections, produces a vast amount of information via road signs and other related outside media which must be communicated to the driver to permit him to reach his destination. Since road signs must serve the whole driver population, the information presented is general in nature. The driver must know his route or consult road maps or other references to determine which exits and turns will take him to his destination. A driver traveling in unfamiliar territory is often faced with uncertainty when approaching an unknown intersection. At present turnpike speeds, with the look angle constantly changing, he may not be able to read the sign at all. Further, the time available to make his decision, move into the appropriate lane, and then execute the required maneuver is extremely short. Any hesitation or delay in decision-making may result in

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missing the turn entirely or cause a driver to make an abrupt change in direction which disrupts normal traffic flow and creates a potentially hazardous situation for other drivers. When traffic is heavy or when adverse environmental conditions, such as glare, darkness, rain, snow or fog prevail, the problem is more serious.

The primary objective of the Bureau of Public Roads' experimental route guidance system is to provide the driver, automatically and within his vehicle, specific directional information that will guide him to his destination over the most efficient routes. Upon interrogation by the vehicle encoded destination signal, route guidance information is received from a roadside computer unit which is part of the integrated ERGS network. This information is decoded and converted into a directional symbol displayed within the vehicle. Previous research by the Bureau of Public Roads led to the adoption of a basic set of 16 directional symbols, 11 of which are directional arrows and 5 are simple two- or three-word instructions (Fig. 1). These symbols are concise and nonambiguous; they represent the simple format required for an efficient visual display.

A research program led to the selection of the head-up display concept as the most effective display method for presenting the directional information to the driver with a minimum of distraction. This paper explains the concept and its advantages, outlines the investigations and engineering tradeoffs involved in selecting a head-up display from various alternative display configurations, and describes the design and operation of a working model built and delivered to the Bureau of Public Roads for evaluation.

HEAD-UP DISPLAY

The term "head-up display" was coined by the aerospace industry to describe a new avionics technique that provides a virtual-image symbolic representation of the visual scene, projected on the aircraft windshield or other partially reflective surface, and superimposed on the real world. This technique has been used to provide target reticles for airborne gunsights, and recently, the aerospace industry has been exploring its tremendous potential as a low-visibility or all-weather landing aid. The displayed symbology, consisting of visual cues, such as the outline of the runway and instrument readings, is focused at infinity and permits the pilot to look at the real world through the windshield and simultaneously obtain instrumental flight control and situation information without lowering his head to look at the instrument panel. Figure 2 shows typical display symbology as seen by the pilot during a landing approach.

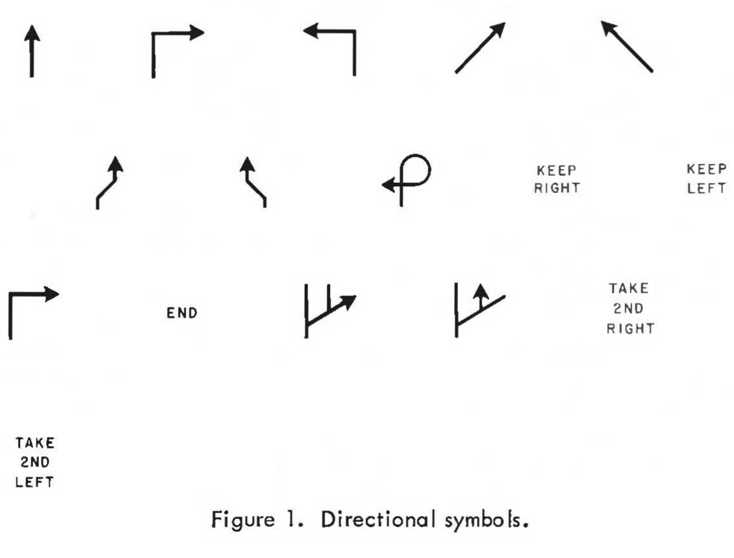
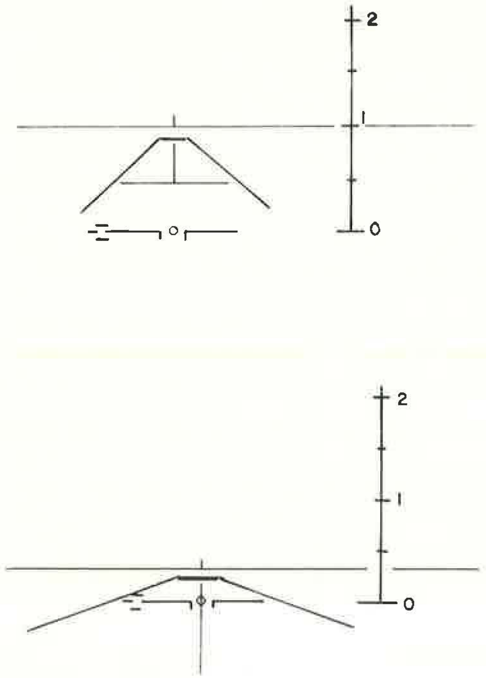


Figure 1. Directional symbols.



Aircraft aligned with runway centerline at 100-ft altitude, approaching runway.

Aircraft over the runway just before touchdown; image adjusts to proper perspective.

Figure 2. Typical head-up display symbology.

This technique is particularly suited for the ERGS application because it offers a distinct advantage over other display methods. The symbology is projected on the windshield in the driver's normal line of vision through a collimating lens system in which light rays reflected from the windshield are essentially parallel. This causes the symbol to appear to be focused at or near infinity and superimposed on the road scene. The driver can observe both the road scene and the symbol simultaneously without refocusing his eyes and with minimum distraction.

DISPLAY REQUIREMENTS

In order to display the symbols so that they could be readily observed and correctly identified by the driver, the symbol characteristics relating to size, stroke width, brightness, contrast ratio and distortion were established by human factors analyses which considered the perceptual limitations of the driver's eye. In addition, other factors influencing the projected symbol design were virtual-image distance, head movement constraints and the effects of vehicle vibration.

The investigations involved a review of published research results in the area of visual acuity and perception. These data were evaluated in terms of the specific application to the route guidance head-up display and resulted in the list of design recommendations given in Table 1. Later validation tests in the laboratory demonstrated that these parametric values will unequivocally allow 99 percent correct symbol identification by the driver in less than 200 milliseconds of display "on" time.

Size and stroke width were selected to insure identification and legibility under low contrast and/or low brightness viewing conditions. Symbol color was selected in the region of the visible spectrum most sensitive to the eye for day as well as night driving. To establish symbol brightness and background contrast ratio, consideration was given to the total driving situation where background illumination may vary from 0.001 ft-L under a moonlit sky, to approximately 10,000 ft-L for fresh snow at midday under

TABLE 1

DESIGN RECOMMENDATIONS FOR HEAD-UP DISPLAY SYSTEM

Parameter	Recommendation
Symbol size	1 in.
Symbol size/strokewidth ratio	5:1 to 6:1
Viewing distance	22 to 28 in.
System vibration tolerance	Approx. 10 min and 30 cps
Symbol luminance requirements	Variable from 1 to 1,000 ft-L
Symbol luminance-background contrast ratio	0.1 minimum
Preferred symbol color	Green region of spectrum, 500-550 mμ
Exit pupil size	8.5 in. horizontal; 4.0 in. vertical
Image location	0 to 4° below the horizontal in the forward plane
Symbol duration	Controlled by driver; could be as short as 200 millisec for recognition

a clear sky. Symbol brightness, variable to about 1,000 ft-L is required for 0.99 identification probability.

Presentation time for the symbol should be of sufficient duration to permit the driver to assimilate the information but not so long as to interfere with visual performance. The tests conducted indicated correct identification was obtained with presentation times of under 200 milliseconds. It appears reasonable to permit the driver to control presentation time.

One of the more critical parameters is the exit pupil size, which determines the amount of lateral and vertical head movement which can be allowed and still keep the driver's eyes in the optical field of view. The head-up display must allow freedom of head movement for normal driver motions and must also accommodate the various sitting heights of different drivers. The diameter of the collimating lens determines the amount of field visible for a given eye position. In the ERGS display a lateral head movement of 10 in. and a vertical head movement of 8 in. would be desirable. However, engineering constraints imposed by specific vehicle dimensions limit the maximum achievable exit pupil size.

ALTERNATIVE DISPLAY CONFIGURATIONS

Various techniques of displaying collimated images were reviewed to determine their applicability to particular requirements of vehicle route guidance. These included most of the aircraft head-up display systems currently being developed by the aerospace industry. Although the airborne systems are too complex and costly to be adapted to vehicle use, the techniques of optical design that made feasible the packaging of the optical elements in a minimum-space envelope were of special interest to the ERGS display application.

Along with space considerations, other factors were important in guiding the selection of a display configuration. Cost is of paramount importance because the route guidance display must be suitable for mass production at the lowest possible cost. Simple and rugged construction, high reliability, easy installation and service are other important factors.

With these guidelines in mind, the investigation proceeded to evaluate alternative configurations in each of the three major functional blocks or subsystems of the head-up display: the optical subsystem, the symbol generation subsystem, and the light source.

OPTICAL SUBSYSTEM

Optical elements in the head-up display include lenses and reflecting surfaces. Since the windshield is partially reflective, it can be used as the final reflecting surface on which the symbol appears. The objective was to select the optical configuration which would produce an image of acceptable quality within the space limitations of the vehicle.

Four collimating viewer designs, identified by the type of collimating lens utilized, were investigated. They are achromatic, plano-convex, lenticular and fresnel. Each was found to have particular advantages and disadvantages.

Achromatic—This design incorporates a compound lens which has the same focal length and the same magnification of light for two different wavelengths and nearly the same focal length for all intervening wavelengths. The achromatic lens exhibited the best resolution when tested, however its required focal length is too long to be compatible with packaging constraints and its exit pupil is limited. Finally, even for the small lens diameter required, the cost is prohibitive.

Plano-Convex—This lens, which is flat on one side and convex on the other, has a practical focal length and is much less costly then the achromatic. However, when tested, this lens, due to its large aperture relative to focal length, exhibited severe spherical aberration. In addition, its excessive weight eliminated it from further consideration.

Lenticular—This lens system consists of a mosaic of 16 lenses, typically in a 4 by 4 matrix molded into one piece of clear plastic. An individual symbol mask and light source would be placed behind each lens. For each symbol to be projected in the same area on the windshield, an optical wedge or prism in the optical path would be required. The drawbacks of this system are high cost, inherent low reliability because of the multiplicity of projection units, and small exit pupil that would severely constrain the driver's head movement. Adjustment of the symbol position on the windshield would be difficult.

Fresnel—This is a flat plastic lens having a number of finely spaced concentric grooves embossed on one surface. Its most desirable quality is large exit pupil size and relatively short focal length. Other advantages are light weight and extremely low cost. It is less fragile than glass and can be easily cut to the elongated rectangular shape required for the head-up display. This lens provided an acceptable image although the quality was not as good as the achromatic. The large exit pupil however provided for comfortable viewing for lateral head movements. On a comparison basis, the fresnel lens offered significant advantages in the areas of cost and packageability and was therefore selected for the head-up display.

SYMBOL GENERATION SUBSYSTEM

Ideally, a symbol generator with no moving parts would be most desirable. The lenticular system meets this objective. However, it cannot be seriously considered because of complexity, high cost, and the extremely high light intensity required for symbol recognition.

Another alternative is to provide a simple mechanical system consisting of a mask, containing the 16 symbols, which is indexed in front of a light source. The symbol mask is driven by a small dc motor. Indexing to a selected symbol is accomplished by a rotating sequence switch.

The latter alternative was selected for the feasibility model as offering low cost, ruggedness, life, reliability, and the least complexity.

LIGHT SOURCE

Use of the rotating symbol wheel permits the incorporation of a single high-intensity light source and a large projection lens to produce an image of the desired symbol compatible with the human factors design criteria (Table 1). This recommended level of maximum symbol luminance of 1,000 ft-L was based on a symbol luminance to background contrast ratio of 0.1 and a background luminance of 10,000 ft-L maximum.

Measurements made inside an automobile, under bright sunlight and high reflection conditions, indicated a maximum level of approximately 5,000 ft-L. It was concluded therefore that for most driving conditions a maximum image brightness of 500-700 ft-L would be sufficient to satisfy the purpose of demonstrating a feasibility model.

Due to the 12-volt operating requirement, it was found that the choice of high candlepower automobile bulbs was quite limited. Two types of single-filament lamps were tested. One, a type 1963 quartz iodine lamp is rated at 100 cp, 75 watts and draws 6.25 amp. The second is a commercially available Type 1195 miniature automobile lamp and is rated at 50 cp, 36 watts and draws 3 amp. Use of a diffuser to eliminate the lamp filament image from showing in the projection reduced the available brightness level by 50 percent. In tests with a diffuser, symbol mask, fresnel lens and simulated windshield, the 100-cp lamp produced a symbol brightness of approximately 1,200 ft-L. The 50-cp lamp produced a symbol brightness of about 750 ft-L which was judged adequate for feasibility model evaluation. The smaller bulb is significantly less costly.

The final results of this evaluation produced the recommended design of the feasibility model head-up display which was to consist of a single bulb light source and diffuser, a motor-driven symbol mask and selector and a fresnel lens projection system.

For the future, some refinements of this design are recommended; however, the basic design approach would be preserved.

FEASIBILITY MODEL

A feasibility model head-up display was constructed and subjected to laboratory and limited field testing to insure that the system produced a symbol image which met the design criteria established by human factors and engineering analyses. This unit was delivered to the Bureau of Public Roads in July 1968 for further evaluation of the display concept in ERGS.

Figures 3 and 4 show the external and internal views of the packaged unit which was designed to be mounted on top of the dashboard of a 1968 Oldsmobile Delmont sedan, selected by the Bureau of Public Roads as the test vehicle. The dashboard unit is entirely self-contained. To keep package size to a minimum, the optical path is folded, i.e., reflected from a mirror. The symbol image is projected through the fresnel lens, mounted vertically (to eliminate glare) on the windshield side. The collimated symbol is then reflected upward by means of an adjustable mirror that can be controlled by a push rod located in the front of the unit. This adjustment accommodates the various driver sitting heights and enables positioning of the symbol on the windshield for comfortable viewing. A dimmer control for symbol brightness is also provided.

The connector receptacle is wired to be directly compatible with the signal lines of the in-vehicle computer-decoder which is being separately developed by the Bureau.

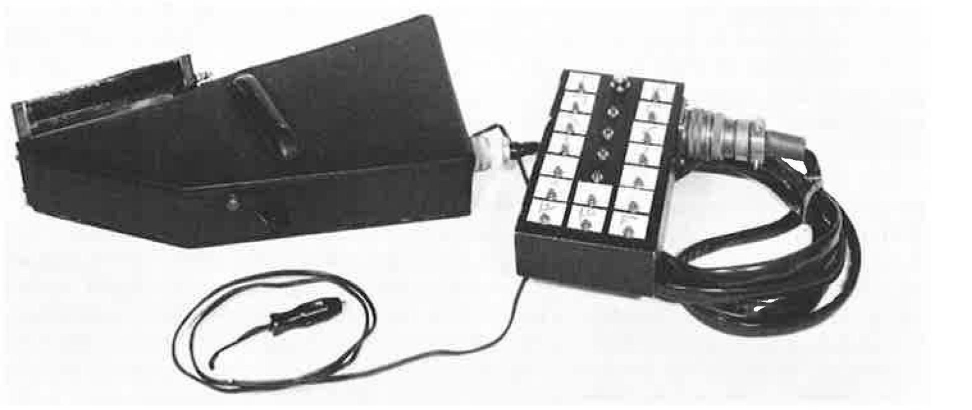


Figure 3. Head-up display, external view.

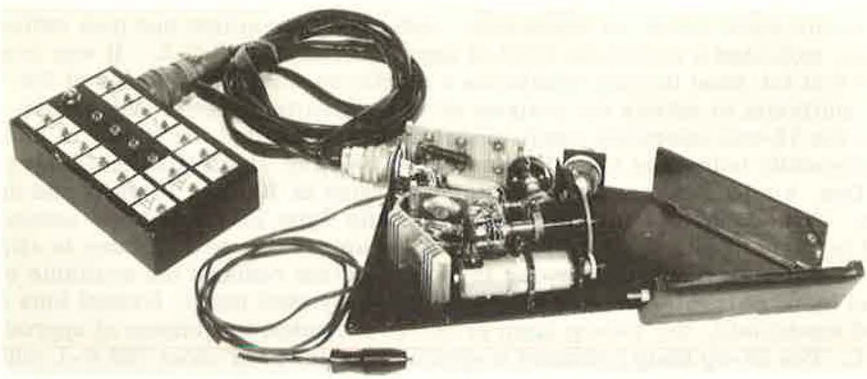


Figure 4. Head-up display, internal view.

For the purpose of feasibility testing, however, the control box was provided to simulate the inputs of the ERGS computer. Sixteen push-button switches, one for each symbol, and an indicator light, which signifies when the projector lamp filament is energized, are provided. During field testing, the evaluator would be seated in the rear seat and could select any desired symbol which would remain in view until the button was released. Testing of various symbol "on" times could thus be accomplished.

The mounted unit does not interfere with normal driving operation and does not obstruct the driver's field of view. Packaging and form factors were subject to constraints due to the specific dimensional limits of the vehicle and the need for an installation that would not require a permanent alteration of the vehicle structure. These constraints on package size limited the size of the lens. The exit pupil, which determines the amount of permissible head movement, was reduced from the recommended 8.5 in. horizontal and 4.0 in. vertical to approximately 6.5 in. horizontal and 2.5 in. vertical.

The requirement to keep the profile of the unit above the dashboard low enough so that it would not obscure any portion of the driver's view of the road restricted the vertical dimension. The acute angle formed by the slanted windshield and the need to keep the fore and aft dimensions from interfering with steering operations correspondingly affected the exit pupil dimensions.

This restriction is not viewed as a hindrance to demonstrating feasibility. However, any production design would give primary consideration to accommodating an exit pupil of approximately 10 in. horizontally by 6 to 8 in. vertically.

RECOMMENDED DESIGN IMPROVEMENTS

The design concept for production units envisions an integrally mounted unit with a larger lens recessed in the dashboard which would provide the required exit pupil size for greater freedom of head movement. Figures 5, 6 and 7 show the prototype under-the-dashboard unit manufactured and installed by Kollsman in the test vehicle.

The projection unit is mounted under the dashboard. A longer optical path than that provided in the feasibility model is incorporated, compatible with the larger lens exit pupil. The intermediate mirror is cold reflective, filtering out the heat produced by sunlight directed through the lens, and thus precluding any damage to the projection unit symbol mask. In future production units, modular packaging techniques would be used to achieve a minimum projection unit package size. The electronics associated with the projection device could be packaged separately in an encapsulated module and mounted in any convenient space. The 12-volt dc stepper motor and sequencing switch used in the feasibility model were selected because of their availability. In the production design, it would be desirable to incorporate a commutator type of symbol selector that would use a low torque drive motor with corresponding cost and weight savings. A singular advantage of the head-up display design is that all of the elec-

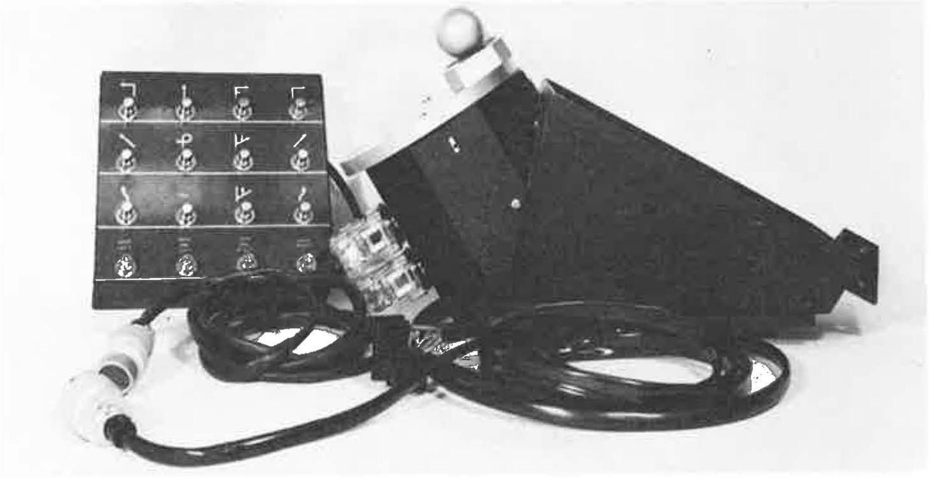


Figure 5. Integral head-up display unit with control box.

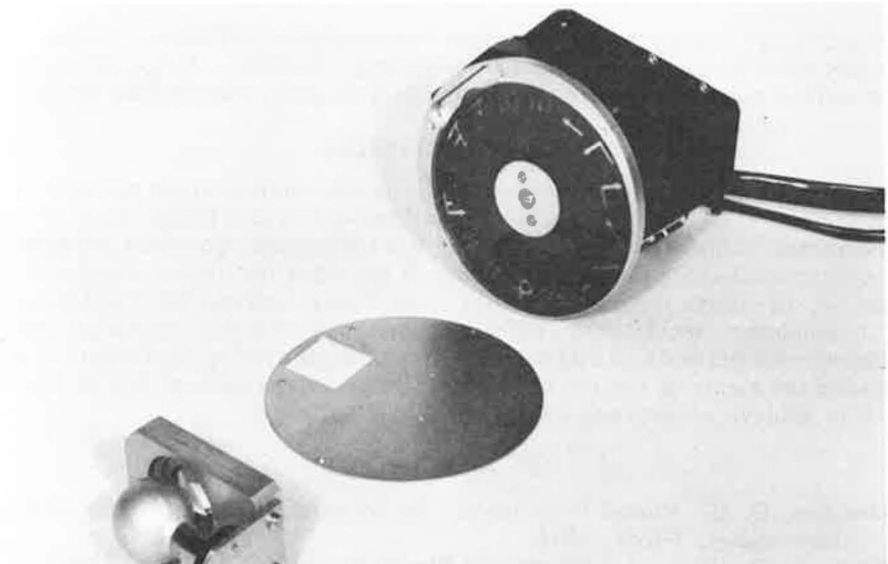


Figure 6. Integral head-up display unit projector and symbol drive assembly.

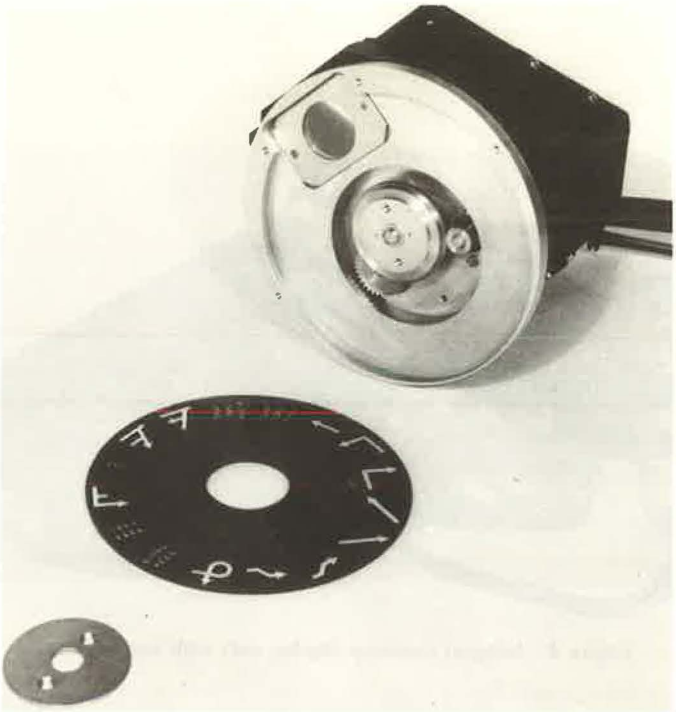


Figure 7. Integral head-up display unit symbol drive assembly.

tronic parts are representative of items commercially available. Lenses and the symbol mask drive motor would be tailored designs. However, large production quantities would reduce their cost to a level consistent with other commercial items.

CONCLUSIONS

The feasibility of projecting route guidance information on an automobile windshield, in the form of directional symbols using a head-up virtual image display technique, has been demonstrated. This type of display has tremendous potential for application to the experimental route guidance system. It provides the driver clear and concise information, in simple format, is easily assimilated, and can be timed to assure proper lead distance for executing turning maneuvers. By reducing confusion and uncertainty, it enhances the driver's ability to achieve maximum driving performance and greatly increases the safety of vehicle operations. The convenience of this device should enable it to achieve widespread acceptance among drivers.

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