# 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

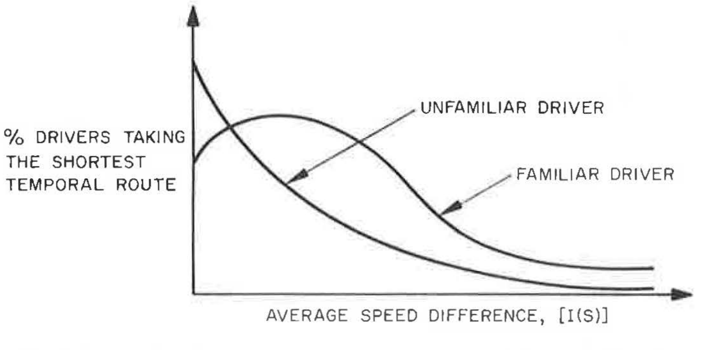


Figure 1. Relationship between driver benefits and highway system impedance.

"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.

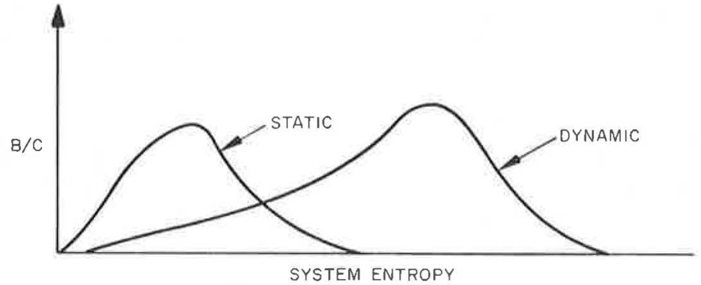


Figure 2. Roadway system value relations.

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

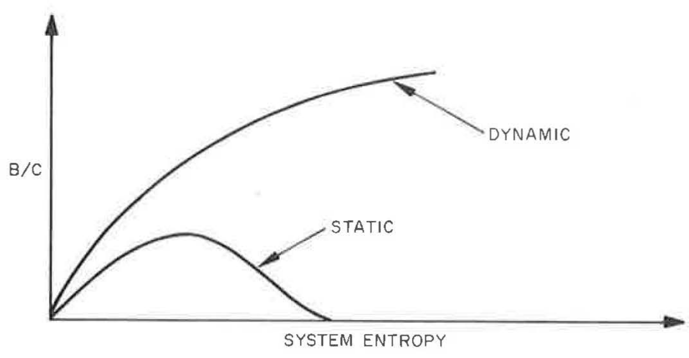


Figure 3. Individual value relations.

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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