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A Research Plan for Highway Vehicle Navigation Technology

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A Research Plan for Highway Vehicle Navigation Technology

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Abstract

This working paper describes a proposed research plan to explore the application of advanced technology to highway vehicle navigation. The proposed research addresses navigation, communication, and control technology, benefits of improved vehicle navigation, system requirements, and design and implementation issues. The paper introduces the issues involved in highway vehicle navigation and communication, and discusses recent developments in vehicle navigation technology.

The importance of a vigorous program of research in this area is identified, and six near term and ten follow-on projects are described, including provision estimates of the level of effort required.

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Preface

The background research and development of a research plan for vehicle navigation technology described in this working paper was performed as part of the ITS Program on Advanced Technology for the Highway (PATH), with financial support from the California Department of Transportation. While it is intended that the proposed research plan serve as guidance in developing future PATH activities, the plan is not intended to imply that all the suggested research be performed by ITS or as part of the PATH program. Similarly, the identification of specific projects is not intended to preclude the repackaging of the proposed research into different projects, as opportunities arise, or indeed the conduct of other research not herein identified.

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1. Introduction

This working paper develops a proposed research plan to assess the technology opportunities for vehicle navigation, and the potential role of vehicle navigation technology in highway automation. As ways are increasingly being sought to allow existing highway systems to handle growing volumes of traffic as efficiently as possible, and the costs of congestion increase, there is growing interest in techniques to improve the operation of the system by providing better route guidance for vehicles. In the longer term, interest in increasing the capacity of the highway system through higher levels of automation raises the question of how vehicles on automatic control would navigate through the system.

Consideration of the issues that arise in proposing the development of a highway vehicle navigation system indicate that much research is needed, in order that systems can be developed that meet the needs of the users in a cost effective way. This research should not only address the necessary technology to be able to perform the navigation tasks, but also attempt to determine the benefits that may result from improving vehicle route guidance and the impacts on the operation of the entire system. Although route guidance has received considerable attention over the past fifteen years, particularly in Europe, the emphasis has been largely placed on developing particular technologies, rather than studying the impact of a particular technology on the operation of the highway system.

Vehicle Navigation

A broad range of navigation tasks can be identified that arise in the operation of highway vehicles. In addition to the general problem of the selection of the best route between a trip origin and destination, particular highway users have specific needs. Emergency services need to respond to unplanned events, which may disrupt the usual pattern of traffic, selecting appropriate vehicles and routes to reach a location as rapidly as possible. Delivery and demand responsive transport services need to consider the interaction between the sequence of stops made by each vehicle and the route selection between stops, while a broader interrelationship exists between vehicle scheduling and navigation tasks. The scale of the navigation task also varies between that required for route selection and the higher precision needed for such tasks as docking and obstacle avoidance.

The navigation task is complicated by the fact that conditions on the highway system may change significantly over time. Since the time at which a vehicle will reach a particular part of the network depends on the conditions on each segment of the route taken at the time that segment is traversed, navigation decisions must consider future changes as well as present conditions. Where the navigation decisions themselves influence the future conditions, such as the routing of traffic around congested areas, a complex dynamic control problem exists.

Vehicle navigation in general can be considered to involve three basic tasks:

1. Determining the current position of the vehicle;
2. Planning a route to be followed from the current position to the intended destination;
3. Monitoring the conformance to the planned route, detecting deviations, and either revising the planned route or taking action to return to the planned route.

Although a route is usually thought of as a path in two dimensional space (or less commonly three dimensions, if multiple levels are possible at the same point), a planned route may also have times associated with various points along the route. These times may include the expected arrival time at a point, or time constraints, such as the latest time at which the vehicle should be at a particular point. The explicit linking of times to points on a planned route is necessary in order to consider the travel time consequences of alternative routes. Thus deviations from a planned route may occur in space or time. Deviations in time may simply cause subsequent time estimates to be revised, or a change in speed to be desired in order to reduce the deviation at subsequent points, or a change of route to be sought. Deviations in space may be due to failure of the control system to maintain the intended route or action by the control system to satisfy other criteria, such as avoiding obstacles or other vehicles. The conformance monitoring task includes deciding when to attempt to return to the original plan and when to initiate a new route planning task (which may result in the plan remaining unchanged).

Determination of position

The problem of determining the position of a moving vehicle has formed the basis of the art of navigation since the earliest times. Position can be determined with reference to an arbitrary coordinate system (such as a reference grid or latitude and longitude) or with reference to fixed points in space. When the vehicle is constrained to travel on a defined route network (as in the case of the highway system), position is generally determined by distance from fixed points along the network (often termed mileposts).

Estimating position between mileposts can be done directly (such as measuring the distance travelled since the last milepost or the current distance to the last or next milepost) or indirectly based on the average speed and time since passing the last milepost.

Current developments in navigation technology based on radio transmissions from fixed stations (e.g. LORAN) or satellites of known position (e.g. Global Positioning System) have provided the capability to determine the position of a vehicle on a continuous basis to a relatively high level of precision in terms of any desired coordinate system (Knoernschild, 1986). However, the cost of this technology has so far prevented its widespread use for highway vehicles, although there are indications that costs may reduce significantly in the future. Even so, as long as the vehicle remains on a known network, it is likely to be more cost effective to determine position by measuring distance and direction travelled.

Measuring distance on a wheeled vehicle is simply a matter of counting wheel rotations, as is currently done by vehicle odometers. Small inaccuracies will arise due to differences in tire size from that assumed, particularly as tires wear, but these can be corrected at the next milepost. However, in order to determine which route is taken at junctions in the network, some way to measure direction is required. Two relatively simple approaches are to use a magnetic compass or to measure the amount of each turn from differences in wheel rotation on either side of the vehicle (differential odometer principle). The magnetic compass has the advantage that it gives absolute direction rather that the relative turn from the approach direction. However, magnetic disturbance due to metal or electrical currents in the vehicle or surroundings can lead to inaccuracies. Because of these errors, it may be necessary for the vehicle to proceed some distance beyond the junction before it is clear which route was taken. Computing the amount of turn from wheel rotations requires accurate measurements of the differential rotation and is open to error from wheel slip. Alternatively, the amount of turn can be computed from measurements of the steering deflection and distance travelled. However, this requires both accurate measurement of the steering angle and the ability to perform continuous calculations to integrate the effect of varying amounts of turn. With both the latter two techniques, it is necessary to have data on the direction of the approach to the junction, although since data on exit direction is required in all three techniques, this does not seem a serious restriction. The relative performance of the two systems would appear to be largely an empirical question determined by the accuracy of the sensors (compass, odometers, and steering angle measurement).

As an alternative to a magnetic compass, a gyroscopic compass could be used. This would avoid the magnetic disturbance and damping problems, but would be more complex mechanically, raising cost and maintenance considerations. Since gyrocompasses incur increasing errors over time (due to gyroscopic precession, friction and other factors) they need to be reset from time to time. This could be accomplished by monitoring progress on the network.

The need to measure direction could be avoided completely if each exit from a junction had a marker with a unique code (at least for that junction) that could be sensed by a vehicle passing over it. Advances in the development of inexpensive magnetic coded markers that can be "read' by a sensor passing nearby and could be glued to the road surface or buried within it may make such an approach feasible for well-defined networks. However, once a vehicle leaves the equipped network, it would need other means to determine direction.

Other, more complex possibilities exist, including radio direction finding and inertial navigation (Hall, 1986), but these are likely to be prohibitively expensive.

Route planning

Highway route planning is a complex problem, although one handled routinely by drivers. Not only may there be multiple criteria to satisfy (such as travel time and operating cost) and a very large number of possible routes, but the consequences of selecting a particular route will depend on how other users of the highway system react to the present and future conditions. It is likely that most drivers adopt a satisficing approach, considering only a limited subset of the more obvious alternatives, selecting what appears to be the best, and sticking to it unless conditions change from those expected by a gross amount.

If conditions on the different links of a network are known (or can be forecast) and do not change with time or traffic volume, algorithms exist to find optimal (defined in some way) paths through the network. Finding optimal paths in networks with characteristics that vary over time and in response to vehicle routing decisions is more difficult, and beyond the current state of the art, except for very simple cases or by making simplifying assumptions.

Vehicle Communication

A navigation system is only as good as the information available to it. In order to make good routing decisions, a navigation system must have reasonably accurate information on conditions on the alternative routes. Since these conditions change continuously, it is necessary to communicate these changes to the vehicle. Given this capability, the question arises how much system knowledge should be stored on the vehicle and how much should be communicated to the vehicle as the need arises. The more knowledge that is stored on the vehicle, the smaller the load on the communication system and the less vulnerable the navigation system is to failures in the communication system. Use of stored knowledge will also permit the navigation system to function in areas where the communication system is not available.

A two-way communication system will also allow the vehicle itself to act as a sensor, providing speed (and potentially density) information on the parts of the route network that it traverses, as well as information on its intended route. This latter information can be used to forecast future traffic conditions on the system.

While broadcast radio is a reasonably effective way to communicate limited amounts of information to a large number of vehicles, communication of large amounts of user-specific information requires a discrete addressing capability and a cellular or direct channel communication system.

The amount of information that can be communicated over a channel in a given period of time depends on the transmission rate and the bandwidth. Transmission rates of digital information are generally measured in bits per second (baud rate). High bandwidth channels allow many messages to be sent simultaneously by restricting each message to a particular frequency spectrum. The use of digital encoding allows higher transmission rates of information than can be achieved with voice channels. For this reason, even voice messages can be digitally encoded for transmission and then decoded for playback at the destination.

Current communication technology makes use of packet switching techniques, in which each message is divided into a number of "packets". Each packet contains information on its origin and destination, as well as other packets in the message. Each node in the communication network can then send the packet on to its destination, and the receiving node can piece the message back together. Thus, not all packets in a given message need follow the same route through the network, permitting efficient use of channel capacity.

Packet switching techniques allow messages to be sent to classes of user as well as discrete destinations. If each user is a node on the network, or is monitoring the flow of packets at a particular node, it can intercept both messages directed to itself specifically as well as to classes of which it is a member (e.g. traffic using a particular link of the highway network).

The nature of communication with a moving vehicle requires an electromagnetic link between the vehicle and a fixed node on the communication network. Possibilities include radio, light, microwaves or magnetic fields. The higher the frequency in the electromagnetic spectrum, the higher the band rate that can be achieved. However, high frequency bands, such as infra-red light, require line-of-sight contact between the vehicle and the fixed node. This, however, permits some degree of selectivity of those receiving the transmission, and helps prevent interference with other transmissions elsewhere on the same frequency band. Selectivity can also be achieved by limiting the power of the transmission, preventing reception by users distant from the node.

Of the techniques so far proposed, four appear to be receiving particular consideration. These are low-power broadcast radio, cellular telephone (a form of broadcast radio that makes use of relatively low powered transmissions, frequency differences in adjacent areas, and techniques to filter out unwanted messages (Cramer, 1986)), infra-red light, and variable magnetic fields with transmitter/detector loops (on the vehicle and buried in the pavement). Each of these techniques has very different baud rate, bandwidth, range, and hardware considerations, as well as potential for electromagnetic interference (either way). Further technology assessment activity is this area appears urgently needed.

Development of a Research Plan

The remainder of this paper establishes the context for a research plan and identifies a program of near term and follow-on tasks, that are proposed as part of the California Program on Advanced Technology for the Highway (PATH), being conducted by the Institute of Transportation Studies. This research is primarily directed at issues affecting vehicle route guidance at a network scale, although it is also intended to provide a technical basis for addressing the other issues discussed above. Considerations of vehicle guidance at a local level, such as lateral control and obstacle avoidance, will be addressed elsewhere in the PATH program.

Chapter 2 provides a brief review of recent developments in vehicle navigation technology, as it relates to route guidance. Chapter 3 discusses a number of considerations that will arise in developing and implementing vehicle navigation systems, and that identify a broad range of research requirements. Finally, chapter 4 outlines a research program and describes a set of initial tasks that could lay the groundwork for a more extensive program of research and development in the future, while chapter 5 contains a summary and conclusion.

2. Recent Developments in Vehicle Route Guidance

The development of techniques for improving driver information and route guidance has received considerable attention over the past few years, particularly in Europe, where research into electronic means for driver assistance is curently being conducted under the multi-national Prometheus program. The need for route guidance was identified over ten years ago (Armstong, 1977), and potential benefits and alternative techniques studied (Jeffery, 1981a,b). Since then, development has continued on different technical aspects.

Alternative Technologies

The simplest approach to route guidance uses conventional broadcast radio messages to advise drivers of highway conditions and recommend routes. The response time of such a system can be improved by using automatic condition monitoring and incident detection equipment to generate appropriate messages to highway authorities and radio stations (Giesa & Everts, 1987). More specific information can be provided through changable message signs, as used in the Japanese CACS system (Yumoto, et al., 1979). Even more detailed information can be provided on a user-specific basis by establishing electronic beacons that communicate with passing vehicles, as in the German ALI-SCOUT and British Autoguide systems.

The display of information to the driver can take the form of simple instructions at each intersection (or significant changes of route) or the use of electronic map displays. The U.S. Etak Navigator system (Jordan, 1986) combines a map display with stored data on the highway network, producing a totally self-contained unit. Route-finding capability can be added to such systems (Tsunoda et al., 1986), although they cannot respond to changing traffic conditions.

CACS

The Comprehensive Automobile Traffic Control System (CACS), sponsor-ed by the Japanese Ministry of International Trade and Industry, has been under development since 1973. Between 1975 and 1976, a pilot sustem was installed in a 28 square kilometer area of Tokyo and put into operation in October 1977 (Yumoto et al., 1979). The pilot system utilized a variety of technology, including digital communication by inductive radio, low power broadcast radio using roadside antennae, and changable message signs.

At 74 intersections and 9 expressway interchanges, about 180 vehicle detectors, consisting of a buried loop or sidefire antenna exchange data with a vehicle antenna located under the rear bumper. The vehicle type, identification number, and destination code are sent from the vehicle to roadside or central computers, and route guidance and driving information are sent in the opposite direction. This information is displayed on a unit in the vehicle that can indicate the entrance lane and exit to take at the next intersection or interchange, using a diagramatic representation of the junction that can display up to seven exits and the appropriate turning movement. Driving information, such as pedestrian crossings, changing road width, or road works, are displayed using characters. A chime is used to indicate warnings or changes in the display. Route guidance tables are updated from time to time and transmitted from a central computer to roadside computers, where they are used to provide guidance to individual vehicles. The roadside computers can recognize public service vehicles and give them priority at signalized intersections.

The roadside radio uses leaky coaxial cable antennae about 400 meters long to broadcast urgent information. The broadcast is received through an adaptor attached to the car radio, and can only be received by vehicles in the vicinity of the antenna. The voice messages are automatically synthesized from information entered at a console by an operator. They are of two priorities, identified by different tones. The highest priority messages override the setting of the car radio, but the lower priority messages can be suppressed by the driver.

Roadside Route Display boards show portions of the network, with link conditions indicated by changing the color of the display, under control of an operator console. Increasing congestion is shown by yellow or red links, while accidents are indicated by a flashing red light.

All three elements of the system are controlled from a single control center, equipped with traffic condition and system status displays and operator consoles. Recent developments (Fujii, 1986) have been directed at improving the communication capabilities of the system.

ALI-SCOUT

This system has been developed in Germany by a consortium of Bosch/Blaupunkt and Siemens, and consists of a unit on the vehicle which maintains a stored representation of the network (von Tomkewitsch, 1986). Network information and route recommendations are transmitted to the vehicle by means of infra-red signals from beacons located at selected traffic signals. This information is then used by the on-board computer to advise the driver of the route to follow. The vehicle keeps track of its position by means of a compass and distance measurements, with errors eliminated by detecting known locations, such as beacons. At each beacon, the vehicle reports the route and time taken from the previous beacon. This information is then integrated with reports from other vehicles to determine conditions on the network.

Because most of the intelligence is located on the vehicle, and each vehicle has a representation of an extensive part of the local network, relatively few beacons are needed. The system could also function in the absence of beacons by reading network data from an on-board storage device (such as a compact disk), although it could not then respond to traffic conditions.

Demonstrations of the system in Berlin and London are planned for early 1988.

Autoguide

The proposed Autoguide system (U.K. DoT, 1986; Jeffery et al., 1987) is similar to ALI-SCOUT, except that the intelligence is located in roadside computers (beacons) at each junction or major intersection, and communication with the vehicle is through small aerials fitted underneath vehicles and inductive loops buried in the road surface. As it approaches an equipped intersection, the vehicle announces its destination, and the roadside computer determines the appropriate route and transmits guidance instructions to get the vehicle to the next beacon. Although costs for the vehicle equipment are expected to be lower than for the ALI-SCOUT system, the

Autoguide system requires more beacons, and the route computer in the vehicle cannot function without the roadside equipment.

Etak Navigator

This system consists of an electronic map display linked to a computer representation of the highway network (Honey, 1986; Dial, 1986). The position of the vehicle is determined by a digitally compensated solid state compass and distance measurement, with errors eliminated at turns on the network by map matching. The map display is adjusted to show the current position of the vehicle.

Although the system does not currently have route finding capability, locations of destinations can be displayed on the map, allowing the driver to select a route. The system requires no roadside equipment, but cannot receive information on traffic conditions nor provide information on travel times to other users. Consideration is being given to the use of cellular telephone to provide a communication capability for exchange of traffic condition and travel time information with a central computer.

Developmental Issues

Although work is proceeding on the development of alternative systems, and various demonstration experiments are currently being planned, there remain many unresolved issues surrounding the appropriate ways to deploy vehicle navigation technology. A recent discussion document on the British Autoguide system (U.K. DoT, 1986) identified the following areas for further examination:

1. Is there sufficient interest in route guidance, both from potential users and suppliers, to justify seeking to set up a system in Britain?
2. Should the Government encourage the development of Autoguide systems requiring electronic signposts, or are self-contained navigation aids the way forward?
3. To what extent should the economic benefits identified by the Transport and Road Research Laboratory affect decisions about the system?
4. How should the trade-off between the amount of intelligence in vehicles and at the roadside be resolved?

5. Is London the natural choice to be the first British city in which to install a viable Autoguide system?
6. Which features of route guidance systems should the Government seek to pursue in an international framework?
7. On what criteria should routes be calculated and offered to users?
8. How should an Autoguide system best be installed, operated and maintained?
9. What powers would be needed to enable the system to proceed? What role should the private sector play in the development of Autoguide?

Other major unresolved issues (Himus, 1986) include the source and coordination of data for coding into the electronic beacons, how the system will anticipate the future traffic conditions that will exist by the time a vehicle reaches a particular part of the network, whether individuals should be able to turn off sensing devices that report vehicle travel times to the system, whether the authorities should have the power to use the system to regulate access to particular locations, and who should decide which routes are made avaialable to system users.

3. Research Considerations

This chapter expands on some of the issues that arise in defining a research plan to explore future vehicle navigation technology. The discussion is intended to establish a context for the research projects identified in chapter 4, and to stimulate reseachers to select topics of interest and develop proposals for future research.

Literature Review

Highway vehicle route guidance and related topics have received considerable attention over the past fifteen years, and a substantial body of literature has developed. Current developments in Europe are likely to add considerably to this literature. It is not the purpose of this section to attempt to summarize this literature, but rather to provide a framework for a review of the literature, which should be undertaken as part of the proposed research program.

Navigation technology

Navigation technology includes techniques for determining the current position of a vehicle, as well as for determining the path to be followed, and displaying guidance information to the operator. A variety of sophisticated techniques for determining position have developed in response to maritime and aviation needs, including the use of radio beacons, inertial platforms, and satellites. While these might find potential use in highway applications, the restrictions imposed by the highway itself combined with the ability to measure distance travelled fairly accurately, has resulted in systems based on measuring the distance from known points along identifiable links of the network. Human drivers place almost total reliance on recognition of visual cues, including signs, to identify position and direction. With increasing automation, attention needs to be given to how a system can identify points it is passing, the links it is travelling on, and the general direction taken.

Vehicle navigation svstems

The current state of the art of vehicle navigation systems has been summarized in the previous chapter. As development of these systems continues, and experience is gained with full-scale testing or commercial operation, additional information will become available. In addition to details of the alternative technologies available, including information on performance and cost, consideration should be given to assessments of the benefits expected or obtained from different systems in particular applications.

Route selection algorithms

While techniques for finding the shortest path through a network are well established, their application to practical navigation systems will raise issues that need special consideration. These include efficient selection of routes on large networks using multiple criteria, such as travel time and cost, particularly when travel times and costs are influenced by traffic conditions on the network. Two other important issues are the identification of driver preference and behavior in route selection and the selection of routes with traffic conditions varying over time.

The identification of driver route selection criteria has been studied by Ratcliffe (1972), Outram & Thompson (1978), and Radovanac & Vukanovic (1985), while studies of routes actually taken have been performed by Wright & Orrom (1976) for an area of central London and by Transportation Planning Associates (1977) and Lunn (1978) for intercity journeys. These studies suggest that drivers behave as if minimizing a combination of time and distance (or out-of-pocket cost), and that considerable variation exists in routes actually followed between any given origin and destination. Further work in this area appears necessary, both in order to better understand how route conditions affect driver preference for routes and how the configuration of the highway system affects the variability in the routes chosen,

Information reauirements and availabilitv

In order for vehicle navigation systems to respond to traffic and highway conditions, appropriate information will need to be collected and integrated. Highway condition monitoring systems have been developed using a variety of techniques to support various traffic control systems. Important considerations include the nature of the data collected and the frequency of the detectors or sensors. The extent and capabilities of existing monitoring systems may significantly affect the cost of implementing a particular navigation system.

Information on the physical configuration of the highway network will also be required in suitable form for incorporation in computer systems. The development of standardized databases by the appropriate authorities will simplify the task of creating and updating the relevant computer files. Consideration will also have to given be to the way in which desinations are identified to the system.

Vehicle communication systems

The range of technologies available for communicating with the vehicles on a network vary from changable message signs and radio broadcasts to vehicle-specific messages using roadside equipment. Selection of appropriate techniques will depend on the associated costs and performance, as well as the amount of data to be transmitted and the ease of installing the necessary equipment.

Technology Assessment

The technology available to support future vehicle navigation systems is continually evolving. Some of the recent and near-term developments have already been discussed in chapter 2. Improvements in related systems, such as highway condition monitoring or vehicle communications, may also be of value to vehicle navigation. In order to take full advantage of the likely future technology, and to understand how best to meet identified requirements, there is a need for a formal assessment and documentation of the relevant technologies. This assessment should not only identify current capabilities and likely future developments, but also estimate the time frame within which the future capabilities are expected to become available.

The technology assessment should consider not only entire systems, but also the technology related to their various components. In particular, the future technology of sensors, microprocessors, and information storage is likely to continue to evolve rapidly, while fiber optic data links are already changing information transmission capabilities.

Vehicle navigation systems

The competing approaches to developing a vehicle navigation system described in chapter 2 are likely to experience continuing improvement as operational experience is gained and new features are added. In addition, new concepts may appear. While this will present a moving target to researchers interested in how the different technologies can be applied, it is important that the current technology is documented as well as possible, and future directions are explored. The competitive and proprietory nature of much of the current activity in these systems may make a sound assessment of both capabilities and weaknesses a demanding task, requiring careful integration of available information, as well as identification and critical analysis of the important issues.

Critical issues that arise in comparing alternative concepts for vehicle navigation include how much intelligence to locate on the vehicle versus the roadside, and how much information to communicate to the vehicle at specific points versus storing on the vehicle. Increasing the on-board capabilities can allow vehicles to obtain benefits in areas where there are limited (or no) support systems, or if the support systems fail in any way. On the other hand, such an approach may be unnecessarily costly when there are large numbers of users. These trade-offs will be significantly affected by the cost and reliability of on-board computing and data storage capabilities on the one hand, and of data communication capabilities on the other.

Another aspect that has apparently received little attention to date is the system/driver interface. As the sophistication and capabilities of the navigation systems increase, the volume of information that must be exchanged with the driver will also increase. Systems requiring the driver to study a visual display or enter data through a keypad have obvious disadvantages in heavy traffic conditions. Voice synthesis and recognition techniques may be an answer, and although the state of the art of voice recognition is not yet adequate for such a task, this is a field that is developing rapidly.

Application to particular markets may require different technology from a general purpose system. Commercial vehicles might benefit from a system that permits messages to be exchanged with company computers, in addition to the exchange of road condition or route information. Pick-up and delivery vehicles may need to enter addresses in the course of a tour to several locations, identify the address location, and replan the route to include the new addresses in the tour. In some urban areas, the capability to locate the closest available parking space to a destination and guide the vehicle to it may eliminate a significant amount of circulating traffic.

Applications to urban transit systems include both locating buses, and possibly determining passenger loads, and estimating deviations from schedule based on current traffic conditions. This information can then be used by dispatch personnel to dispatch additional vehicles or reschedule vehicles currently on the system, and instructions can be transmitted to the relevant vehicles.

Highway condition monitoring and forecasting

While a vehicle navigation system that is based on average or expected traffic conditions on the network may provide some benefits to the user, the ability to react to changing conditions during the course of the trip should provide significantly enhanced benefits. For this to occur, it will be necessary to monitor current conditions, project how these conditions are expected to change in the near future, and transmit this information to the navigation systems. Although considerable effort has been directed at highway condition monitoring, for use in existing traffic control applications, there is potential for significant improvement in the areas of both monitoring and forecasting.

Current technology uses detection loops or interrupted beams at discrete locations to measure vehicle passage and sometimes speed (Jeng & May, 1984). While these techniques can provide a measure of traffic flow conditions, which can be used to detect downstream incidents and obtain estimates of link travel times, they do not provide direct travel time measurements and cannot determine the nature of incidents. They are also less effective with multi-lane flows, and turning movements at intersections. Detection loops and beams can be supplemented by closed circuit television

(CCTV) cameras and displays, which allow traffic control personnel to study traffic conditions in more detail, and determine the nature of specific incidents. However, the large number of CCTV cameras required to provide adequate coverage for a large network is obviously expensive, and requires human monitors to interpret the information displayed. If this information is to be used by a computerized vehicle navigation system, it has to be expressed in an usable format and entered into the system, requiring additional human intervention.

The introduction of vehicle navigation technology that involves communication between the vehicles and a roadside system, in a way that allows the vehicles themselves to report travel times and traffic flow conditions offers additional possibilities for highway condition monitoring. Individual vehicle identification and tracking, using such techniques as electronic transponders, magnetic identification codes, or optically scanned labels, can be used to measure travel times, as well as determine flow patterns, although there are significant privacy issues that arise.

As the number and variety of sensors employed in monitoring a given highway network increase, automation will be needed to manage, interpret and integrate the large flow of data generated. This may be a suitable area for the application of several artificial intelligence techniques, including computer vision and expert systems. While the monitoring of current conditions is a necessary condition to effective vehicle navigation, the prediction of how the conditions will change by the time a given vehicle reaches a particular location is equally important. This prediction requires not only an understanding of the dynamics of traffic flow and the destination patterns of the current system users, but also an understanding of how these users will react to the evolving conditions, and in particular how this behavior will be affected by the information provided. This will require more sophisticated modelling than is currently possible. Apart from the development of appropriate models, the scale of the modelling task may require much greater computer capacity than has been traditionally used in urban traffic modelling. Advances in computational techniques for supercomputers and parallel computers, that are being developed for such applications as fluid mechanics and finite element analysis, may prove useful for large scale network modelling.

Vehicle communication svstems

The ability to communicate with individual vehicles is critical to a navigation system that can react in real time to changing traffic conditions. The number of vehicles involved in the highway system restricts the use of voice radio to the broadcast of general information. Even so, this requires the driver to select the appropriate information and somehow enter it in the vehicle's navigation system. The transmission of digitally encoded information over a radio or cellular telephone channel could both increase the volume of information possible, and provide for automatic selection and storage. Broadcast messages can be supplemented by changable message and direction signs. These can provide site-specific information as well as route guidance to all relevant vehicles at the required location, without burdening other vehicles with irrelevant information. However, the amount of information that can be given is restricted by the fact that a driver may only see the sign for a few seconds. Thus broadcast information and changable signs should be considered supplementary techniques.

The use of fixed beacons to transmit selected information to passing vehicles, using such techniques as infrared signals (as in the German ALI-SCOUT system) or electro-magnetic fields (as proposed for the British Autoguide system), can reduce the amount of information that must be received by each vehicle, particularly if the vehicle can use the same technology to identify itself or its destination to the beacon before receiving the information. However, such systems require relatively expensive equipment on the vehicles, are no use to vehicles not so equipped, and only work where the beacons have been installed. In contrast, a system based on voice radio can be used by any vehicle with a suitable radio receiver (in practice almost every vehicle), and a single transmitter can cover a very wide area. More selective coverage can be provided by allocating specific frequencies to different parts of the network, while the number of frequencies required and the problem of selecting the correct one can be reduced through the use of cellular radio.

Selection of appropriate communication systems for specific applications will depend both on the costs and capabilities of the different systems, as well as the number of vehicles affected and the amount of information that is required to be transmitted, Where communication technology is likely to be installed for other reasons, such as cellular telephone, its adaption to the receiving of navigation information may be relatively inexpensive. Because of these opportunities, as well as the interrelation between the navigation technology and the amount of information needed, the design of navigation systems should give careful consideration to the range of alternatives for vehicle communication. Ideally, a vehicle navigation system should be adaptable to a wide range of communications technologies, from driver input of broadcast information to automatic communication with roadside beacons. Such a system would be usable in a wide range of environments, and could provide incremental benefits to the users as the roadside systems are developed.

Benefits of Improved Vehicle Navigation Technology

In order to compare the merits of alternative vehicle navigation systems or to determine the economic feasibility of a particular system, it is necessary to understand the nature and magnitude of the benefits to highway users and others of improved navigation capability. Research in this area will need to identify the various types of benefit that can arise from such a system, as well as determine the nature and size of potential markets for the technology. While estimates can be made of the total potential benefits if all vehicles were to be equipped with a particular technology (perhaps adjusted for market penetration), in practice it is not likely that all vehicle owners would find any given system worth installing. Indeed, it is quite likely that different systems would be attractive to different types of user, suggesting that several systems might eventually find separate markets. At the same time, any given system is not likely to be equally effective in all geographical areas. Thus in order to obtain better estimates of the potential benefits, as well as take account of the economics of implementation, it is necessary to understand the usefulness of particular features in terms of the potential markets that the technology might serve.

Identification of benefits

In considering the benefits that result from improved vehicle routing, it should not be forgotten that some people may be worse off. Certainly, those who live, shop, or work along routes that receive increased traffic as a result of the changed traffic patterns are affected by all the disbenefits that increased traffic volumes bring. Also the travel times and fuel consumption of those vehicles that used less busy routes that now receive more traffic will increase. While these increases have been included in the net effect calculated for the network as a whole, there are important distributional questions as well as issues resulting from possible variations in the value of travel time.

Thus, ideally, it is important to identify not only the total savings in travel time, operating costs, or whatever, but also the distribution of those changes, and in particular who gains and who loses. Nor can it be assumed that if such changes are implemented on a wide scale, other economic factors will remain unchanged. If travel times between residential areas and employment centers are improved, land values can be expected to adjust to reflect the changed market. Thus while a commuter may save travel time and operating costs, some of these savings will be absorbed in higher rent or mortgage payments. Similarly, property values in those areas receiving heavier traffic, or with increased travel times, are likely to drop relative to those areas that have experienced improved conditions. While society as a whole gains the full amount of the net savings, some of these savings become transfer payments to (or from) property owners. Whether such windfall changes are viewed as beneficial or not is likely to be highly situation specific.

Recent experience in the U.S. and many other developed countries regarding public concern over the traffic impacts of proposed developments indicates that these considerations are likely to be impose significant political constraints on the large scale implementation of vehicle routing technology. This discussion suggests two related, but separate, research topics. One is the development of analytical models to better understand the relationship between network travel times and land values. The other is to identify ways in which the impacts of traffic rerouting can be mitigated, so that the gainers can compensate the losers sufficiently to permit the changes to occur. Since these mitigation costs may be a significant fraction of the total cost of implementing a particular system, they may affect not only the implementation feasibility, but the design of the entire system. In some cases they may be so high that rerouting traffic is not economically feasible.

Potential markets

The concept of a market for a new technology refers to any group of potential users that have some common characteristics. In the case of vehicle navigation, the relevant user characteristics include the geographical area in which the vehicle trips are made, the nature of the trips, and the type of organization or individual owning the vehicle. For a particular market to be viable, the users have to make enough trips during which vehicle routing benefits result to offset the cost of installing and operating the equipment. The more expensive the equipment, the larger will have to be the number of trips and/or the benefit per trip.

In defining potential markets, it may be useful to separate commercial use from personal use. Use by commercial vehicles is likely to be directly related to the operating cost savings involved, including vehicle utilization and crew time. Driver preference issues, such as avoiding stop-start traffic conditions, are likely to be less important. Pick up and delivery functions, particularly those in which the routes change from day to day and cover a wide area, are likely to benefit most from navigation assistance. Where drivers are unfamiliar with the local street system, they may not only waste time searching for addresses, but are more likely to remain on congested major streets than attempt to save time by taking short cuts through unfamiliar territory.

This suggests that an important research activity consists of examining different types of commercial operation, in order to identify the potential savings of improved routing information, and developing relationships between readily obtainable measures of firm size and nature of activity (such as number of employees and SIC code) and type and amount of trips.

In considering personal use of vehicle navigation systems, the "gimic factor" should not be overlooked. People may purchase systems even if no objective benefits in terms of travel time or cost can be demonstrated. They may simply enjoy the novelty of receiving the information in the vehicle, or wish to impress others with their technological sophistication. Of course, they may also perceive that they obtain travel benefits, even if they do not, or may be persuaded by the marketing activities of system vendors that they do. Since individual purchases will rarely have access to the analytical resources of transportation planners, in practice these issues of perception of benefits may be far more important to purchase decisions that the objective situation. Since such purchase decisions will ultimately affect the success of any system, this aspect clearly deserves further study.

Assessment of scale of potential benefits

Once a particular market has been identified, the process of assessing the magnitude of the potential benefits from the introduction of a particular navigation technology involves two aspects: determining the changes in resources used and impacts generated, and placing a value on those changes. This assessment will have to consider the pace at which the navigation technology might be introduced, as well as changes in the manner of operation of the market that might arise as a result of the implementation of the technology.

The two principal factors affecting changes in resource use are the distance travelled and the travel time. The distance travelled will affect vehicle operating costs, although the cost per mile is also a function of traffic conditions. Traffic conditions will also affect the external impacts of a given number of vehicle miles of travel, including noise and emissions. In particular stop/start driving conditions associated with heavy traffic congestion increase fuel consumption and maintenance costs, as well as engine emissions. The determination of the changes in resource use and impacts for a particular traffic pattern on a given network will require appropriate network analysis tools, with sophisticated link performance functions. Such a tool would obviously have other applications in the areas of project evaluation or traffic impact assessment, although as yet does not appear to be readily available.

Once estimates of the changes in use of each resource have been made, it is usually necessary to assign a dollar value to these changes, so that they can be combined, and the net benefits can be compared to the costs involved in implementing the system. While operating costs can be valued at market prices, determining the value of non-market items, such as noise or air quality is more difficult. These problems have been extensively addressed in the literature on transportation project evaluation, and although standard values are published by various government agencies for use in project evaluation (e.g. AASHTO, 1977 and U.K. DoT, 1980), these figures are frequently questioned by economists and others. In particular, the use of system-wide average values may introduce significant bias when used for a market-specific assessment. Since the conclusions drawn by any evaluation study depend on the values assumed, the values used should always be clearly stated, and sensitivity tests performed to examine the impact of varying the assumptions. In order to ensure consistency between different studies, standard values should probably be adopted. However, these should be carefully examined for application to the particular conditions under study and guidance offered for ranges to be used for sensitivity testing. A review of recent literature in the area would probably be helpful, and it may be worthwhile, or even necessary, to perform local studies to determine appropriate values for specific markets. As other studies in the program proceed, opportunities to obtain empirical estimates of values of non-market resources in the course of other work should be actively pursued.

Requirements Analysis

The development of a successful vehicle navigation system should be based on a careful analysis of user requirements. While it is possible to develop a particular technology and then see if there is a market for it, this is a rather risky approach. Even if the resulting system proves economically viable, it may include fairly costly features that contribute little or no improvements in performance, thereby reducing the overall benefits of the system, or excluding potential users.

While automatic vehicle control may be some way in the future, consideration should also be given to how a particular vehicle navigation technology might be integrated into a future vehicle control system. The extent to which the navigation system can provide some of the technological building blocks for an automated control system, such as on-board computer capabilities and vehicle/roadside communication, may greatly influence the ease with which such a system could be developed.

Identification of potential users

Since any navigation system will only be purchased if it meets the needs of its potential users, and these needs are likely to vary widely from individual to individual, it is necessary to identify particular markets, or groups of users, and analyze the specific requirements of each. It may be possible to define a system that meets enough needs of many such markets that a single, standard system can be developed. However, it is more likely that several systems, or variants on a basic system, will be required.

Two large potential markets consist of urban commuters and commercial pick-up and delivery vehicles. While the commuters make the same trip each day, and may be quite familiar with alternative routes, they can benefit from real-time information on congestion, in order to select the best route. Commercial vehicle drivers, on the other hand, may vary their route from day to day, be unfamiliar with a particular area, and have a number of destinations, which can be visited in varying order. They may also be less concerned about the exact arrival time at a particular destination than the commuter, who wishes not to be late for work, but may be more concerned with the vehicle operating cost. They may also have restrictions on possible routes, due to the vehicle size.

A third market consists of what may be termed non-commercial itinerant travel, such a recreational trips. Such drivers may be in quite unfamiliar areas, but have a relatively low value of time and not willing to pay much for minor savings of travel time. They may also have trip-specific route preference factors, such as quiet or scenic roads. The relatively low density of traffic in such environments may demand a system with small costs for roadside equipment.

Commercial itinerant travel, such as long distance trucking, is likely to place greater importance on time and cost savings, although vehicle size restrictions and the need to reduce adverse impacts of heavy vehicles on unsuitable roads and particular communities may restrict alternative routes.

User needs assessment

Assessment of the needs of a particular group of potential users involves both identifying the issues of concern and obtaining measurements of the magnitudes of the factors involved. These factors include the frequency with which trips are made, as well as the characteristics of these trips, such as the distribution of distances and travel times, and the typical conditions on the network over which the trips are made. Further research is needed on the way in which drivers make choices between the characteristics of alternative routes, such as distance and travel time, for different types of trip.

Very limited data are currently available on routes actually taken by drivers. British estimates of the benefits of route guidance (Jeffery, 1981a) have been obtained by extrapolation to a national level from a single survey in a largely rural area in Gloucestershire (Transportation Planning Associates, 1977). Current U.S. estimates (King & Mast, 1987) are based on similar extrapolations. While some useful data can be extracted from past surveys, such as the 1981 Bay Area home interview survey conducted to support the development of the regional transportation demand models (Reynolds et al., 1981), the generally limited information in such surveys on the details of the routes taken, let alone the reasons for selecting particular routes, suggests that extensive additional surveys will be needed.

The level of detail with which route guidance should be given to the driver may vary with application and knowledge of the area, while the amount of advance warning needed for a turning movement or change of route may vary with traffic conditions. Different drivers may need the same information expressed in different ways, in order to be comprehensible.

Constraints

Constraints on the development of a vehicle navigation system can take several forms. One set pertains to the performance capabilities of the available technology. In particular, communication rate and reliability between the vehicle and roadside equipment, information storage and processing on the vehicle, and communication with the driver are likely to be critical issues. Equipment to be installed on vehicles should be small enough to be conveniently retrofitted to existing cars, and external units need to be robust and conform to conventional vehicle design. A second set of constraints arise from human factors considerations. If the navigation system is to be used while driving in heavy traffic, the way in which information is provided to and requested from the driver must be compatible with the driving task and the possible noise and lighting environment. The designation of destinations by the driver must conform to the way in which the driver usually expresses such information, or at least not require unusual knowledge or complex transformations.

A third set of constraints are created by the nature of the trips being undertaken and the configuration of and conditions on the highway network. The frequency and detail of driver guidance will need to be much greater in a dense urban street network than on a regional expressway system. Restrictions on access for particular vehicles, or at particular times, will reduce available routes, while unavoidable bottlenecks, such as tunnels and bridges, may significantly reduce the benefits of seeking alternative routes.

Information needs and communication

The amount of information required by a proposed navigation system will vary from application to application. Consideration needs to be given to the level of detail with which the highway network is represented, including whether individual lanes are identified, and how much information on traffic flow conditions is available. While simplified networks may be useful for some applications, others may require detailed representation down to individual street, particularly if there are one-way circulation patterns or access restrictions. The denser the network, the greater the number of alternative routes that can be identified. While this may increase the benefits of the system, it will require much greater amounts of information on traffic conditions to be useful as well as greater computational effort.

As the amount of information required by the system increases, so the communication needs between the different components change. The appropriate method of communication, between the traffic condition sensors and central computers, between central computers and roadside equipment, and between roadside equipment and vehicles, depends on the volume of information to be handled. Where many vehicles may be communicating with a single roadside facility at one time, adequate capacity or suitable demand management techniques must be available to handle peak conditions.

Computational and data storage reauirements

The computational and data storage requirements, either in the roadside equipment or on the vehicle, will depend on both the allocation of the analytical tasks between the vehicle and roadside equipment and the complexity of the navigational tasks. Task complexity will be affected by the size and density of the network, as well as the level of detail of traffic condition information and the sophistication of the route finding algorithms. The data storage requirements on the vehicle will depend in part on the communication cababilities discussed above, since certain information can either be stored permanently on the vehicle or stored on roadside equipment and requested when needed. If the information is stored on the vehicle, consideration must be given to how it is originally loaded and revised when necessary.

Need for further research

The definition of the functional requirements for an operationally and economically viable system may identify needs for improved technology, either to increase component performance or to reduce costs. These needs may become apparent from the technology assessment, from parametric studies conducted as part of the requirements analysis, or from experimental prototype development. In order to fully understand both the performance requirements in an operational environment and the capabilities of available technology, it will be necessary to conduct a series of computer simulations and a program of prototype experimentation and testing. The computer simulations are not only generally less costly than full-scale hardware testing, but can be used to investigate aspects that are not possible to test without a fully developed system. They can also be used to explore such aspects as the impact of hardware performance improvements that have not yet been achieved. Component and prototype testing is necessary both to validate the computer analysis and to identify unforeseen issues that may arise.

Design Issues

Once the functional requirements of a vehicle navigation system have been determined, a number of detailed design issues arise that will require additional research to resolve. These include the best configuration for an operational system, and ways to ensure the most efficient and robust operation.

Location of computation activity

An important design decision involves how much computation activity to place on the vehicle and how much in roadside or central facilities. Reducing the computation on the vehicle requires less sophisticated on-board equipment and reduces the amount of information that must be communicated to the vehicle. More powerful roadside or central computers may not only be able to identify alternative routes faster, but can reduce the duplication involved in route-finding by vehicles with similar destinations. They may also be able to identify situations in which user optimum routes differ from system optimum routes, and adjust routes accordingly. However, increasing the computation on the vehicle provides greater flexibility to operate in different environments or with varying amounts of support information. It may also provide the vehicle with the capability to perform other tasks, unrelated to the navigation system, or permit modification of the algorithms or navigation functions to individual needs.

Efficient transfer of information

In view of the large amount of information that will have to be transferred between components of the system, particularly that may have to be communicated to the vehicles, efficient ways to encode this information are required. Standard coding and communication protocols will need to be developed and agreed, so that vehicles can exchange information with different systems. This will extend to network definition, so that partial network information, such as traffic condition reports, can be integrated with network descriptions stored in memory.

Robustness to incomplete information

Route finding algorithms will be required that are robust to incomplete or inaccurate information. Errors may arise from highway monitoring sensors, forecasted conditions may not evolve as expected, data may be lost or garbled in transmission, or information may not be available for parts of the network, particularly in the early stages of implementation. Such problems should be largely invisible to the driver, and while they may result in sub-optimal routes, they should not produce wild deviations or grossly inefficient routes.

Interaction with traffic management control systems

With the increasing development of traffic management control systems, from freeway ramp metering to traffic signal coordination, the design of vehicle navigation systems should permit interaction between such control systems and the route selection process for individual vehicles. This will require the control system to communicate its objectives to the navigation system so that the two do not work at cross purposes. At the same time, the communication of intended routes from the navigation system to the control system could improve the traffic management process.

Distributed versus centralized decisionmaking

Selection of vehicle routes or projection of future traffic conditions can be performed using a distributed or centralized approach. The implementation of these alternative concepts can vary with the specific configuration of the system, ranging from a single central computer receiving direct input from the highway condition monitoring sensors, selecting routes and communicating with each vehicle via a system of beacons, to a network of roadside computers receiving input from local sensors and sharing this information with each other and with each vehicle in its area, leaving the vehicles to determine their own routes. In practice, the need to provide some level of systemwide control on the one hand and reduce the scale and complexity of the task on the other is likely to result in a hybrid concept with some centralized functions and some distributed functions. Determining the appropriate allocation of functions and the specific structure of the distributed elements of the system will require further research and careful planning for each application.

Use of vehicles as sensors

Since the vehicles themselves are moving on the network and can communicate with the information distribution system, they can be used as sensors to measure and report traffic flow conditions. With even a relatively small proportion of the vehicle mix performing this function, a very high level of coverage of the entire network can be obtained, as well as information not available from fixed sensors, such as speed profiles. This approach has been adopted in the German ALI-SCOUT system, with vehicles reporting travel times between beacons. The design of the system will affect what information is potentially available, and how selectively it can be obtained.

Incorporation of learning ability

A vehicle navigation system can not only have access to a large amount of information about traffic patterns and highway conditions, but can have the capability to measure how travel times on particular routes compared to those expected by the system in planning the route. The design of the system could take advantage of the potential to learn from this experience. Although the incorporation of such a learning ability is not a necessary aspect of a navigation system, it could significantly enhance the system performance over time, particularly if only a small part of the traffic on the highway system is equipped to participate. Development of appropriate learning techniques could constitute an important research activity.

Technology Implementation

The implementation of a particular vehicle navigation technology involves more than the technical questions of how best to design and construct the system. Since these issues may affect the design of the system, it is important that they be explored in parallel with the technological development. Complex systems, particularly ones of the scale required for vehicle navigation in large metropolitan areas, are rarely implemented in one sweep, and involve many different institutions and organizations. These frequently have conflicting objectives, that may have to be resolved before any progress can be made. Progressive implementation over a period of time requires the system to be viable while only partially complete. These aspects are often less well understood than the technical issues.

Identification of alternative implementation pathways

There are usually many different ways to implement a particular technology. These can vary on the basis of location, markets served, financing arrangements, and responsible organizations. An important issue with large public systems, such as the highway system, is the respective roles of the public and private sector. Private sector organizations may have easier access to investment capital, provided the project is financially viable at an early stage, but may lack the authority to erect necessary facilities and the mechanisms to restrict access to those paying for the benefits. Public sector agencies, on the other hand, do not have problems with monopoly power, can obtain powers to take actions in the public good, and can use taxation to generate revenues for projects that produce social benefits.

The choice between different implementation paths is not simply a question of what achieves the end result at least cost, or produces most benefits, although these are important considerations, but should address social policy objectives, so that the system is implemented in a way that contributes toward, rather than detracts from, other societal goals. Important among these are likely to be issues of income distribution, employment opportunity, economic growth, and land use. Where legal or regulatory changes are required for a particular implementation path, consideration should be given both to the delays that this might encounter, as well as the desirability of the changes in and of themselves.

Relationship to hinhwav automation

Although vehicle navigation can be pursued as a goal in itself, the benefits that are likely to be achieved, while great numerically, are not large in relation to the scale of the highway system expenditures as a whole. In order to gain significant increases in highway system productivity, it will be necessary to seek additional technological improvements. Although the benefits of higher levels of automation have not been definitively established, this is an obvious path to pursue. Such automation will clearly require a vehicle navigation capability. It is therefore desirable that the development of vehicle navigation systems be done with one eye on the evolving technology for highway automation, not just in terms of the compatibility of the technology and the ability to use the navigation system infrastructure for developments in vehicle control, but also to better understand implementation issues.

Identification of institutional and regulator-v constraints

Major changes to existing systems inevitably encounter problems from institutional and regulatory structures that were established to handle different situations. These can be overcome by a combination of modifying the existing structures and modifying the proposed change to avoid the constraint. In the case of vehicle navigation systems, difficulties are likely to arise from jurisdictional responsibilities of different levels of government. In the U.S., as in many other countries, operation of the primary highway system is a state responsibility, while local roads and streets are the responsibility of lower levels of government: counties, cities and towns. The existence of regional transportation planning agencies in large metropolitan areas adds a further complication. In such a situation, it is not clear which would be the appropriate agency to install beacons and roadside equipment on both primary highways and local streets. Yet effective selection of alternative routes to avoid congestion would involve use of all classes of highway. One solution might be to establish a special purpose agency for regional traffic control, although this would require existing agencies to give up some of their authority. In view of likely community concerns over the impacts of the diversion of traffic from primary highways to local streets, this may be a difficult issue.

Another set of issues are likely to arise over mechanisms to finance vehicle navigation facilities and charge for their use. Paying for the facilities through general road user taxes may be unpopular with those who do not acquire the equipment, while charging users for actual use is likely to be cumbersome and add a significant overhead cost. One solution might be a license fee or tax on vehicular equipment, although appropriate provisions would have to be devised to ensure payment.

The identification and assessment of these and other related issues forms an important step in the development of an implementable plan.

4. Proposed Research Plan

It is clear from the foregoing discussion that adequate resources to address all the many issues to be explored in the area of vehicle navigation technology would greatly exceed the likely availability of research funding under the PATH program. Nor is it necessary that all research questions be addressed at once, or by the PATH program itself. Research in many of the issues is being actively pursued by other organizations, and it is only necessary for the PATH program to follow the progress of this research. Furthermore, until a better understanding of some of the issues is obtained, it may be premature to being exploring others in any detail.

The proposed research plan therefore identifies a number of research projects that could be funded in the near term, and that would provide a basis for future work, together with estimates of the level of effort that might be appropriate for each. The plan also identifies a larger number of follow-on projects, that could build on this near term work and ultimately lead to demonstrations and field evaluations of particular technologies.

Preliminary estimates of level of effort have been made for the proposed near term projects. These estimates have been made on the basis of the duration of the project and the size of the research team, including professional research staff and graduate student assistants. Person-months of effort were then converted into dollars using standard rates for faculty investigators, research staff and student assistants, and factored up by a standard amount to cover non-technical support staff, and other direct and indirect costs, including supplies, computer time, travel and overhead. The rates assumed for the calculations are shown in Table 4.1. Since the projects are of different duration, and may be programmed in different order, depending on funding and personnel availability, all estimates have been made in 1988 dollars. While these estimates are useful for program planning, they will need to be refined once individual investigators develop proposals and prepare more detailed work plans.

The proposed near term program will require approximately $270,000 over a 2 to 3 year period.

Table 4.1

Assumed Unit Costs for Project Budgets
(1988 $)

Salary (FTE)	$/month
Faculty investigator (Reg. 4)	6,000
Research staff	4,000
Student assistants	1,800
Benefits	% salary
Faculty investigator	20
Research staff	29
Student assistants	2
Secretarial support	10 % research personnel costs
Supplies and expenses	10 % research personnel costs
ORS charges	5 % other direct costs
Indirect costs	47 % total direct costs

No estimates have been made for the appropriate level of effort for each of the follow-on projects, since this will be determined in part by the results of the near term research and the availability of research funding, as well as the results of other research that may have been performed elsewhere in the meantime. However, assuming that individual projects are of a similar scale to the larger of the near term projects, each project is likely to cost between $50,000 and $150,000 (in 1988 dollars). Funding all of the follow-on projects identified might therefore cost in the region of $1.0 million over a 3 to 5 year period, exclusive of major hardware acquisition.

Near Term Projects

The proposed near term program consists of the following projects:

1. **Review of the state of the art of vehicle navigation technology.** This review should examine the available literature discussed in the previous chapters and prepare annotated bibliographies and a summary of the current state of the art.

   The research should include the following tasks:

   a) Review and update the PATH bibliographic database in the area of vehicle navigation technology and related issues, such as highway condition monitoring and vehicle communication.

   b) Review available literature at appropriate levels of detail, and prepare annotated bibliographies.

   c) Prepare a state of the art review, documenting the available technologies, implementation experience, and principal research issues identified in the literature.

Duration:	6 months
Level of effort:	0.5 months FTE faculty investigator
	3.0 months FTE student assistants
	$17,000

2. **Development of network analysis tools and a sample network for route choice and benefit assessment studies.** In order to conduct empirical

studies of the potential benefits of alternative navigation technologies, and to evaluate alternative systems, it will be necessary to develop a computer model of a sample network, together with associated analysis tools. In addition to conventional path finding and traffic assignment routines, these tools should include link performance functions that can compute travel time, operating costs, noise, emissions, etc., as a function of traffic conditions on the link. Ideally, these functions should be validated through a comparison of simulation of a real network with empirical observations.

For ease of data acquisition, the sample network could be based on the Bay Area, and could utilize existing network models developed by the Metropolitan Transportation Commission and others. The network should be capable of use at varying levels of detail, depending on the application, from the regional freeway and arterial system to individual local streets. It is probably only necessary to model selected areas at the finer detail.

The research should include the following tasks:

a) Examine the requirements of potential applications of the network model and develop software and data specifications.

b) Investigate existing analysis tools and data sources, and determine whether these can be used or modified.

c) Acquire, install and modify as necessary network data and analysis software.

d) Develop additional required software.

e) Prepare user and technical documentation.

Duration:	15 months
Level of effort:	2.0 months FTE faculty investigators
	6.0 months FTE research staff
	9.0 months FTE student assistants
	$115,000

3. Determination of parameter values for user and social cost functions. The evaluation of the costs and benefits of alternative vehicle navigation technologies requires values for the various components of user and social cost, including travel time, vehicle operation, noise, etc. While this need arises in all types of project evaluation, and standard values are available from various sources (e.g. AASHTO, 1977), there is a large body of literature on the subject and a broad range of possible values. Nor is it clear that typical values commonly used are appropriate for situations likely to be encountered in vehicle routing applications. In any event, existing values need to be updated to reflect changes in income and prices, and to incorporate the findings of more recent research.

In order that evaluations are performed on a consistent basis, it is desirable that a recommended set of values are available, together with guidance in their use. These values and procedures will also be of use in other PATH programs.

The research should include the following tasks:

a) Review the recent literature on the valuation of user and social costs, as they pertain to highway projects, and summarize the values obtained.

b) Investigate how the situations experienced in different route selection problems may affect the pattern of costs experienced by users or others.

c) Prepare recommended values for assessing user and social costs, and guidelines for their use.

Duration:	12 months
Level of effort:	1.0 months FTE faculty investigators
	6.5 months FTE student assistants
	$35,000

4. Review of time-dependent routing algorithms. The selection of paths through a network when the conditions on the network are changing with time is not well understood. In order that further work on routing algorithms is based on the best available techniques, there is a need to summarize the current state of knowledge of the topic, and identify where additional work is required.

The research should include the following tasks:

a) Review the recent literature on time-dependent network analysis and summarize the available techniques and experience with their application.

b) Assess the strengths and limitations of the alternative techniques, determine their potential application to vehicle navigation problems, and identify the need for further research.

Duration: 9 months

Level of effort: 0.5 months FTE faculty investigator
4.5 months FTE student assistants
$22,000

5. Identification of specialized markets for vehicle navigation technology. The user requirements of particular markets are likely to vary widely, depending on the trip frequency and characteristics. In order to understand how different vehicle navigation technologies might be appropriate for different markets, and to assess the scale of the potential market for a particular technology, it is necessary to identify as many of these potential markets as possible, and determine their characteristics and size.

One approach to identifying such markets consists of examining the trip-making patterns of households and different types of organization or firms in different sectors of the economy. By considering the types of trip where navigational assistance may be beneficial, and identifying the amount of such trip-making by particular classes of household or organization, different markets can be identified and their scale assessed.

The research should include the following tasks:

a) Identify the characteristics of vehicle trips where navigational assistance may be beneficial.

b) Identify and review data sources on trip-making characteristics of households and organizations.

c) Analyze data on trip-making by class of household or type of organization to identify potential markets for navigation technology.

d) Assess the scale of potential markets, at both regional and national levels, using demographic and economic data to estimate numbers of vehicles and volume of travel.

Duration:	6 months
Level of effort:	0.5 months FTE faculty investigator
	3.0 months FTE students assistants
	$17,000

6. **Preliminary assessment of potential benefits of vehicle navigation technology in selected markets.** Using the network analysis tools developed in Task 2, the user and social cost parameter values developed in Task 3, and the information on potential markets developed in Task 5, it should be possible to begin to assess the potential benefits of vehicle navigation technology. For reasons of resource constraints, as well as data limitations and uncertainty over the costs and performance of particular technologies, this initial assessment will have to be restricted to selected markets, and is unlikely to produce definitive conclusions. The objective is to better understand the issues affecting the viability of navigation systems and obtain preliminary estimates of the likely scale of benefits.

For reasons of data availability, as well as relevance to future operational experiments, the markets to be analyzed will be located in California.

The research should include the following tasks:

a) Identify selected markets to analyze, based on a review of previous research and available data and analysis tools.

b) Define the navigation technologies to be investigated and determine how to represent the application of these technologies in the context of the modelling approach adopted.

c) Design and conduct a series of experiments using appropriate network analysis models, in order to estimate the impacts of alternative technologies on system users and others. The experiments should consider different levels of adoption of each technology and varying traffic conditions.

d) Evaluate the magnitudes of the benefits and costs to both system users and others, and assess their distributional impacts.

e) Identify areas of uncertainty, methodological difficulties, data deficiencies, and need for further research.

Duration:	12 months
Level of effort:	1.0 months F'TE faculty investigators
	3.0 months FTE research staff
	6.5 months FTE student assistants
	$64,000

Follow-on Projects

A potential program of follow-on research includes the following projects:

1. **Technology assessment of highway vehicle navigation systems.** **A** more comprehensive examination of current and future technological capabilities than was possible in the near term projects would address real-time vehicle communication, highway condition monitoring, on-board computation and mass data storage, and driver interface requirements.

2. **Investigation of the data transfer requirements of alternative vehicle navigation technologies.** Computer simulation techniques could be used to explore the volume and rate of data transfer as a function of the system configuration and traffic density.

3. **Comparative evaluation of on-board versus roadside computation capability.** Computer simulation and parametric analysis could be used to determine performance requirements and comparative economics for different system configurations.

4. **Identification of driver route choice criteria.** Further empirical research is needed on how drivers select routes, and trade off different aspects, such as time and distance.

5. **Development of route selection algorithms.** Algorithms are needed to handle route selection with multiple criteria, to take account of time varying conditions and the equilibrium effects of route decisions for other vehicles, and account for incomplete or uncertain information.

6. **Development of techniques for forecasting future traffic conditions.** Expert systems and other modelling techniques could be applied to predicting the interaction of traffic flow dynamics and driver behavior.

7. **Comparative assessment of the potential benefits of alternative vehicle navigation technologies in selected California markets.** This research would extend the earlier work into new markets and incorporate methodological refinements and better understanding of system technologies.

8. **Investigation of legal and institutional issues in the implementation of vehicle navigation technologies.** This research should address the legal authority for implementing navigation systems and jurisdictional responsibilities, as well as the relationship between navigation systems and traffic management systems, and the powers of police and highway authorities to intervene in the operation of the system.

9. **Investigation of pricing strategies for the recovery of system costs, and impacts on system deployment and effectiveness.** Research results on user benefits could be combined with economic modelling techniques to study the impacts of alternative pricing strategies.

10. **Design and conduct of full-scale experiments.** Commercially available or prototype hardware could be used to conduct experiments with volunteer (or paid) drivers or fleet vehicles to validate the results of analytical studies.

5. Summary and Conclusion

Recent advances in the technology of highway vehicle navigation have provided the opportunity to implement large scale vehicle guidance systems in the very near future. Such systems are currently being actively developed in at least two European countries, and full scale experiments are being planned to take place within the next twelve months. However, there are many unanswered questions about how best to deploy such technology, how effectively it may be used to address traffic capacity problems in urban areas, what problems are likely to arise with widespread use of vehicle navigation systems, the comparative advantages and disadvantages of different systems, or even what further technological development is required to make any of the proposed systems work.

A vigorous program of research is necessary in order both to take full advantage of the developing technology and to anticipate future problems in a timely way. This working paper provides a background discussion of relevant issues and outlines the proposed components of such a program. In the near term the following research projects are proposed:

1. Review of the state of the art of vehicle navigation technology.
2. Development of network analysis tools and a sample network for route choice and benefit assessment studies.
3. Determination of parameter values for user and social cost functions.
4. Review of time-dependent routing algorithms.
5. Identification of specialized markets for vehicle navigation technology.
6. Preliminary assessment of potential benefits of vehicle navigation technology in selected markets.

It is anticipated that this program could be completed within a period of 2 to 3 years at an estimated cost of 270,000 1988 dollars.

A potential program of follow-on research has also been identified, consisting of the following projects:

1. Technology assessment of highway vehicle navigation systems.
2. Investigation of the data transfer requirements of alternative vehicle navigation technologies.

3. Comparative evaluation of on-board versus roadside computation capability.
4. Identification of driver route choice criteria.
5. Development of route selection algorithms.
6. Development of techniques for forecasting future traffic conditions.
7. Comparative assessment of the potential benefits of alternative vehicle navigation technologies in selected California markets.
8. Investigation of legal and institutional issues in the implementation of vehicle navigation technologies.
9. Investigation of pricing strategies for the recovery of system costs, and impacts on system deployment and effectiveness.
10. Design and conduct of full-scale experiments.

Such a program might take from 3 to 5 years and cost of the order of 1 million 1988 dollars, exclusive of any major costs involved in developing or acquiring hardware for full-scale experiments.

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