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ROUTE GUIDANCE SYSTEMS FOR IMPROVING URBAN TRAVEL AND LOCATION CHOICES

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Abstract—Recent technological advances in navigation systems for private vehicles have the capability to provide drivers with highway route information on a dashboard-mounted video display screen. These technological advances, together with two-way radio communication of digital information, automatic measurement of traffic flows, and supercomputer technology, could be combined to provide useful information to drivers concerning expected travel times, best routes, and best departure times. This paper reviews the status of this technology and explores the information and prediction requirements for the computer models required to implement such a system. Research needed to evaluate the potential impact of such a system is also described.

INTRODUCTION

A concerted effort to improve urban traffic conditions has been made in large urban centers of both developed and developing regions of the world during the past 40 years. Massive expenditures on freeways and public transit lines have transformed street and streetcar systems into modern, high-speed expressway and rapid transit networks. Automobiles have been greatly improved with regard to safety, operating efficiency, and atmospheric emissions, while maintaining the high level of performance and comfort desired by consumers. Traffic signal systems have been improved in terms of their level of automation and response to traffic conditions; a detailed survey of advanced traffic control systems and recent experience with their application is given by Strobel (1982). The design of roadways, parking garages, and other facilities has been upgraded in terms of performance, cost, and aesthetic attributes. Finally, the capability to predict future use of proposed facilities has advanced to the point that it may truly be regarded as a science.

Despite these advances, urban traffic congestion remains a pervasive, negative feature of the urban condition, especially in areas undergoing rapid development. Newspaper editors of major cities crusade about the need for relief. Opinion surveys indicate a general dissatisfaction with traffic conditions, and often compare them unfavorably with the problems of crime, access to health care, housing conditions, and so forth. A recent report of the (U.S.) Engineering Research Board (1987) cites urban traffic congestion as one of the most important transportation problems requiring research.

Urban transportation planners and researchers generally agree that the phenomenon of traffic congestion is reasonably well understood and that the present programs of road improvement and operation are cost-effective and appropriate. Few would argue for a major program of new urban expressway construction, since the social and environmental consequences appear to be far more severe than the benefits to motorists; newer suburban areas, however, are seriously deficient in both arterial street and expressway capacity.

Likewise, there is a general reluctance to recommend construction of major rapid transit systems, except in very large cities, since their cost seems highly excessive as compared with the expected level of use. A moderate level of traffic congestion is not only a characteristic of a viable urban city, but may even be beneficial in terms of reducing trips of excessive length, encouraging the use of alternate modes, and emphasizing the importance of urban travel in housing and job location choices (Boyce and Kim, 1987).

Still, one wonders whether the conventional wisdom concerning these issues and their present solutions is correct. Why is it that other fields such as telephone communication, television, computers, and even electric power generation and transmission have made major technological advances during the past 40 years, whereas urban transportation technology has remained basically static? Is it simply that urban transportation technology has fully matured with little possibility for further advancement? Clearly, the advances that were cited earlier are limited to the level of components or subcomponents, as described by Garrison (1984). Is there no system-level innovation or technological development that could raise the productivity of the entire urban transportation system to a new, previously uncontemplated level of efficiency?

During the past year, I have been exploring and rethinking this issue, stimulated largely by requests to prepare papers examining the future of automobile technology. In doing so, I first became aware of a recent technological innovation being marketed as a navigational aid to drivers. Recalling a workshop discussion chaired by Hearn (1985), I considered how this navigational aid might be combined with current communication and traffic monitoring technology, and with present and prospective analytical

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capability to identify network routings that are best from either an individual user's or society's point of view. Could this system, once implemented, achieve the increase in productivity and relief from inefficiency that is often requested? What increases in traffic operations efficiency might be expected from the full implementation of such a system? How would these changes, and the improved level of travel information that might accompany them, influence travel choices beyond route choice, such as choice of departure time, trip frequency, and even the choice of alternative modes? How might this system change the choice of housing and job location choices, or the choice of shopping and recreational travel? What would be the benefits to users of a partial system implementation?

These seemed to me to be the questions that require examination concerning such a system. I then began to explore what has been happening with regard to the development of this technology. Somewhat to my surprise, I learned that much has been done and is currently underway, especially concerning the development of hardware. It is less surprising, however, that the most difficult analytical issues have not been addressed in any depth.

In this paper I will integrate what I have learned recently on the issue of route guidance system technology with my thinking on an advanced route guidance system incorporating concepts of dynamic route choice in a congested network. The emphasis in this paper is on use of automobiles for commuting trips. Another important application of the technology described concerns routing of truck trips; however, this aspect is not considered further here.

The remainder of the paper is organized as follows. First, a review of route guidance system technology is presented. Second, the use of on-board navigators in conjunction with advanced communication technology and computers is examined. Then, travel behavior of urban commuters is examined to determine how this emerging technology would affect their travel and location choices, and what differences it could make. The assumptions and limitations of this current analytical framework are also examined to determine whether it is suitable for answering the questions. Finally, a refined set of questions stated in the terminology of this framework is offered.

A REVIEW OF AUTOMOBILE NAVIGATION TECHNOLOGY

An overview of the history and current status of the field of automobile and truck navigation is provided by two review papers by French (1986a, 1986b). The first concerted research effort to develop a vehicle navigation system was the five-phase program to develop an electronic route guidance system (ERGS), undertaken by the Bureau of Public Roads of the U.S. Department of Transportation in 1967 (Rosen *et al.*, 1970). The first three phases were completed before the project was terminated in 1970.

The ERGS system design identified two vehicle routing problems: (1) the "static" problem of informing unfamiliar drivers of the best route through a highway network to a specified destination without regard to traffic conditions; and (2) the "dynamic" problem of informing familiar as well as unfamiliar drivers of minimum-time routes, taking into account traffic and other conditions that are varying with time. The system design required hardware components in participating vehicles and at instrumented intersections. The vehicular components were to consist of a console containing a destination encoder and control logic, communication and display circuitry, a visual display with audio-alert signal, and trigger and communication antennas. The roadside components at each intersection were to consist of a destination decoder, control logic, and a communication/buffer storage unit and trigger and communication antennas for each approach lane.

Detailed descriptions of the system design, which was developed by General Motors Research Laboratories under contract to the Bureau of Public Roads, are given by Rosen *et al.* (1970). The system design also specified software for finding the required best routes by applying minimum path algorithms to network representations of the highway system. This information was to have been transmitted to the intersection-based decoders for transmission to the vehicles.

In view of their emphasis on the so-called dynamic route guidance problem, it is interesting to note the authors' comments in 1970, when algorithms for solving network equilibrium models with constant origin–destination (O–D) flow rates had only recently been devised (Dafermos and Sparrow, 1969; Bruynooghe *et al.*, 1970): "Efficient algorithms, which can handle large networks and the great amount of data thus implied, will have to be developed. Strategies must be developed to route only the correct proportion of drivers via parallel routes. . . Also envisioned is a methodology for acquiring O–D data from roadside units and forecasting real time demand on network links. Demand would be compared to capacity, and routing strategies would operate to maintain traffic flow below the link breakdown volume. . . . Obviously much research is still required to develop the software that would operate such a sophisticated information and control system." (Rosen *et al.*, 1970, p. 152). Despite major advances in network equilibrium models since 1970, the problems described remain largely unsolved today.

Following the demise of ERGS, research and development of automobile route guidance systems was pursued in Japan and the Federal Republic of Germany. These developments are now briefly described, especially with regard to dynamic route guidance.

The Japan Ministry of International Trade and

Industry carried out the Comprehensive Automobile Traffic Control (CACS) Project from 1973 to 1979 at a cost of seven billion yen (about U.S.$30 million). Descriptions of the project were presented by Yumoto *et al.* (1979) and Fujii (1986). The overall objective of the project was to develop an integrated system for optimal route guidance, diversion of traffic from highly polluted areas, priority access by public service vehicles, advanced display of traffic regulations, and alerts and simultaneous communication for use in an emergency (Yumoto *et al.*, 1979). A pilot system, operated from 1977 to 1979, consisted of a two-way digital communication link by inductive radio in the vicinity of a roadway antenna, ground-to-vehicle communication by roadside radio transmission to vehicles, and roadside visual displays.

A system for computing routing alternatives from each intersection to a specified destination was devised and implemented. To reduce the computational effort, the network was approximated by a hexagonal grid except in the vicinity of the origin. The system determined routing alternatives to each destination from each intersection. Evidently, the routings did not consider current traffic flows. An evaluation of the system for four O–D pairs in an area of Tokyo estimated that travel time could be reduced by 11%.

Following the completion of the pilot project, the JSK Foundation was established by the Japan Ministry of International Trade and Industry and private investors to develop the system further and expedite its introduction into use. An experimental system was established in Tsukuba in 1985 to field-test various technologies developed by JSK. The principal emphasis seems to be on the development of protocols for digital communication systems.

In the Federal Republic of Germany, the ALI Destination Guidance System was designed primarily for freeway guidance by the Blaupunkt/Bosch Group according to French (1986a). ALI uses induction loops at roadway intersections to collect speed and destination data from vehicles equipped to use the System. Optimal routes for these destinations are computed centrally, transmitted to these vehicles, and presented in visual form as turning instructions. A field test in 1979–1982 covering 150 km of the FRG autobahn network demonstrated that the system worked very well (Zechnall, 1986). The system has not been introduced, however, because of the high cost of installing the roadway devices. A second generation system known as ALI–SCOUT is being field tested in West Berlin beginning in 1987 (French, 1986b).

Various on-board vehicle navigator systems have been developed by automobile and electronic manufacturers in Japan, Germany, and the United States. This review will focus on the first commercially available automobile navigation technology, known as the Etak Navigator. The Etak system uses a magnetic compass as well as a differential odometer to determine direction and distance travelled, by which location may be determined by "dead-reckoning." Digital map data stored on tape cassettes are input to an on-board computer similar to an IBM PC in capacity, and displayed on a CRT. The vehicle's location is "matched" to the map and displayed. As the vehicle is driven, the map scrolls across the CRT and the vehicle's location remains stationary in the center. An input destination can also be displayed.

The system has been introduced in the San Francisco and Los Angeles areas and has received substantial publicity. The cost of the system is approximately $2,000 (French, 1986a; Zygmont, 1986). The system does not involve radio communication or route information advice. An advanced version of the system described by Dial (1987) includes these features, as does the following system which I initially described in Boyce (1986).

TOWARDS AN ADVANCED ROUTE GUIDANCE SYSTEM

What additional technology would be necessary to extend the navigational aids described above into an *advanced route guidance system*? First, a communication system is needed. A radio receiver would enable the navigator to receive digital information on the best available routes from a specific origin to a specific destination, as well as current and future travel time estimates. For the purposes of this paper, it is assumed that this information could be provided for sufficiently small origin and destination areas so as to yield meaningful routings. Adding a radio transmitter could enable a central controller to receive O–D and departure time information. Moreover, from reports of the vehicle's location en route, additional data on vehicle demand could be obtained. Alternately, O–D and departure time information could be transmitted by telephone prior to departure.

Second, a comprehensive traffic monitoring system is required. Elements of this system are already in place in the form of expressway flow monitoring systems and traffic signal sensors. New systems based on high-speed processing of video images of traffic flows are under development (Hoose and Willumsen, 1987). Data from these sources would be transmitted to a central analysis unit for the purpose of estimating travel times on all network links. Historical data could also be utilized. Travel times over alternative routes between hundreds of thousands of O–D pairs would be evaluated, and best route information transmitted to the vehicle-based navigators. This information would need to be updated very frequently, perhaps as often as every five minutes.

The third component of the system is the central analysis unit. It would consist of one or more large computers, probably of the multiprocessor supercomputer type. Travel time and vehicle flow infor-

mation from the traffic monitoring system would be used to calculate shortest time routes, or to determine the travel time over precalculated alternative routes, whichever proved to be more efficient. (Average vehicle operating cost could also be included in determining best routes, but for simplicity routes are described in terms of time.) If O–D data for current and prospective trips were available, together with recent historical data, expected shortest routes for several departure times at intervals of perhaps 10 minutes could also be calculated. These estimates could be used by drivers to decide their best departure times, or to avoid unusual conditions caused by accidents or other traffic flow interruptions.

These three subsystems (communication, traffic monitoring, and computation) together with the navigator location sensing and display subsystem constitute the proposed *advanced route guidance system*. A somewhat similar but more comprehensive technological system concept, Automobile Road Information System Evolution (ARISE), has been described by a group of Swedish experts. A feasibility study made by ConNova (1985) concluded that such a system could be cost-effective, especially if an integrated system for route guidance and dynamic system management could be achieved. The PROMETHEUS research program is an even more ambitious effort aimed at solving these problems (Daimler-Benz, 1987). The following sections speculate on the implications of such systems for urban travel and location behavior and for reducing traffic congestion.

A FRAMEWORK FOR ANALYZING THE IMPACTS OF AN ADVANCED ROUTE GUIDANCE SYSTEM

How would the system described above change the use of the urban transportation system by commuters? Is it possible to predict in advance of the partial or full deployment of such a system whether it would reduce travel time and congestion? These are questions for which transportation network modelers should be able to offer insights, if not complete answers. In this section, an initial framework for addressing these issues is described.

The classic transportation network equilibrium model of Beckmann *et al.* (1956) relates flow-dependent travel times to route choices and travel demands on a highway network. In its simplest form for a fixed rate of trips per time period from each origin to each destination, the model states that the flow-dependent travel times on routes that are used are equal and that no unused route has a lower travel time. Thus, each driver is on a minimum travel time route. In this model the route travel times are determined as increasing functions of the flows on the links comprising each route.

A serious shortcoming of existing models concerns the representation of links and link travel time functions in such models; generally, links are currently defined as road segments *between* intersections, and delays at intersections are largely ignored. To be useful for a route guidance system, link definitions need to be intersection-based and take account of the effects of opposing flows on delays (Boyce *et al.*, 1987). The solution of this model formulation, in turn, requires the use of an asymmetric route choice algorithm (Dafermos, 1982); to date, no large-scale models of this type have been solved.

The model makes two rather strong assumptions. First, it is a static, rate of flow model. All variables are expressed in trips per time period, and the implied duration of the flows is sufficiently long that the flow of trips from each origin to destination occurs on each link of each used route. In other words, there is no concept of a vehicle moving through the network in this model; rather, there are vehicle flows per time period on routes and links.

If such models are to be used to predict route conditions over a dynamically changing commuting period, clearly a static model is unacceptable. Current research to develop dynamic models, however, suggests these models are presently intractable for networks of rather modest size (Ben-Akiva *et al.*, 1986). A solution to this issue may lie in a quasi-dynamic approach. One example of a quasi-dynamic model is described by van Vliet (1982, p. 580).

An alternative approach would consist of dividing the overall commuting period into relatively short time periods of perhaps 10 minutes. If O–D tables of vehicle flows appropriate to each time period were available, then the solution of the model would correspond to travel conditions during each short time interval. Clearly, each O–D table could not contain trips longer than 10 minutes in duration; therefore, it must contain segments of longer trips which would occur during the short period under consideration. A way to segment longer trips has been defined in a preliminary formulation (Boyce, 1987); current research is investigating solution methods for this quasi-dynamic approach.

A second assumption of the network equilibrium model is that drivers have perfect information; that is, somehow they "know" which routes to use. Horowitz (1984) has investigated a model in which drivers are assumed to acquire this information through their prior commuting experience; even assuming this information, he finds it cannot be shown that the flows will converge to a stable equilibrium. The proposed auto guidance system would have the capability of providing much better information than is presently available, such as the highly summarized traffic advisories broadcast by radio stations. The proposed system may be a way to assure that equilibrium solutions can actually be achieved.

The imperfect information presently available results in longer trips than a system with perfect information, which are termed *user-optimal* in that each driver is on his/her shortest route. In a system with less than perfect information, some drivers are bound to take longer routes, thereby not only in-

creasing their travel time, but also the travel time of others through the congestion they add to the system.

The classic user-optimal network equilibrium model, in fact, may be generalized to include the dispersion in choices to longer routes resulting from imperfect information. This model is generally not applied because there presently exists no efficient way of fully or even partially enumerating the set of candidate routes between each O–D pair. Moreover, since no data exists on actual route choices on urban networks, and little data on total travel time, there is presently no good basis for implementing such a *dispersed* network equilibrium model. Nevertheless, in the context of the questions raised in this paper, some estimates of the savings in travel time from improved route information could be made using these models.

One further point should be made with regard to a user-optimal equilibrium. It is a property of the solution of the model for a congested network that the number of used routes for most O–D pairs is greater than one. This multiple route property may be expected to hold for user-optimal flows in the real world as it presently does for dispersed flows. Thus, a route guidance system instructing all drivers from each origin to each destination to follow *one route* would actually increase congestion, even if the origins and destinations were quite small areas. Hence, another operational question requiring investigation concerns how to allocate drivers to multiple, equal time routes. But before this question is addressed, it should be analyzed to what extent multiple routes are used in the solution of the user-optimal model and how the number of routes depends on zone size and the level of congestion.

As already noted, the user-optimal network equilibrium for a congested urban network has the property that each driver follows a shortest route. However, this solution does not minimize the total travel time of all drivers except in the uninteresting case that link travel times are fixed. The model in which the total travel time is minimized results in *system-optimal* route choices. In this solution each driver follows a minimum marginal travel time route, that is, a route in which the driver's travel time plus the additional time he/she imposes on other drivers is minimized. The system-optimal solution may result in drivers between some O–D pairs following longer routes in order to reduce total travel time. With a route guidance system, these drivers could be advised which routes to follow in order to reduce total congestion.

What is not known about the system-optimal solution is how much it could reduce total travel time. Clearly, the extent of the reduction depends on the level of congestion. In a very congested network, the savings may be sufficiently large that the "longer" minimum marginal time routes of the system-optimal solution may be shorter than the user-optimal routes for many O–D pairs. If this were true and the differences were reasonably large, there would be a very strong incentive for drivers to cooperate to achieve a system-optimal solution. Without the advice from the route guidance system, however, they would be unable to do so. The time incentive could be strengthened by a system of user tolls dependent on the time loss each driver imposes on the other drivers (Vickery, 1965). Investigating the magnitude of the time difference between system- and user-optimal solutions is clearly a researchable question. Until now, however, it has been a question of only hypothetical interest.

IMPLICATIONS FOR CHOICE OF DEPARTURE TIME, MODE, AND LOCATION

The route guidance system also has profound implications for travel choices other than the route of travel. Improved travel time information would tend to improve other travel choices as well. Most important among these is the time of departure. In some cases it may be possible for a driver to delay his/her departure time and actually arrive earlier or at least avoid unpleasant driving conditions. An ability to predict route travel times to a destination for a fixed arrival time would permit a driver to optimize the time of his/her departure, thereby probably helping to reduce the level of congestion. This feature of the system implies a predictive capability as well as a real time monitoring component. Such a capability would seem feasible to develop by using historical data from recent days combined with a predictive model of choice of departure time.

Commuters consider many factors in choosing between the use of their private automobile vs. public transit modes. One of these factors is the travel time of the journey, which they may tend to underestimate for auto and overestimate for transit. By improving the quality of travel time information for both auto and transit, the route guidance system would allow commuters to improve their choices so as to raise their overall utility. For highly congested routes, this information might result in more use of public transit. The information from the system might also enable transit operations planners to make transit services more competitive.

Choice of residential and job location is also partially influenced by commuting time and cost. While the true extent of the effect of commuting time on these locational choices is unknown, it is widely believed to be important in determining the general area in which to conduct a detailed housing or job search. Although public transit timetables provide information on commuting times, travel times by automobile to alternative locations may be unknown and seem likely to be underestimated. The availability of information on auto commuting times to alternative locations might well result in households choosing residences with lower travel times than would otherwise be the case. The same remark

would apply to choices of job location for persons with multiple employment opportunities, such as salespersons, some office workers, and assembly line workers.

IMPACTS ON THE OPERATION OF THE HIGHWAY SYSTEM

It was suggested above that the auto travel time information would be useful to transit planners in offering more competitive services. The estimates of route and link flows would also be useful to traffic engineers in optimizing the timing of the traffic signal system and in the overall design of the traffic control system. The state-of-the-art of traffic signal system timing is that signals are optimized for fixed traffic flows. The problem of optimal settings when the flows are user-optimal, for example, is unsolved and extremely difficult in a mathematical sense. The opportunity to draw on route choice information, either in a historical or real time sense, could substantially improve the traffic engineer's capability to optimize the signal system. The travel time savings from this effort are also unknown, but could equal or exceed those of improved route information.

BENEFITS FROM A PARTIALLY IMPLEMENTED SYSTEM

One attractive feature of the system described is that a partial implementation of the system could yield substantial benefits concurrently with research and development of the full system. A first generation system might consist of (1) calculation of shortest routes using flow measurement equipment and historical data and (2) transmission and display of this information on vehicle navigator systems. The same information would be available on especially equipped television receivers in homes and offices. This partial system would provide travel time and route information for a specified origin and destination on request.

An enhancement of this system could use historical data to provide short-run forecasts of shortest routes and travel times. This enhanced system might display likely shortest routes and times at 15 minute intervals through the peak commuting period. Both of the systems described so far would utilize only digital radio receivers in the vehicles, a requirement that seems both feasible and cost-effective in view of recent advances in cellular radio technology.

A second generation route guidance system could utilize data transmitted from the vehicles. Initially, only a small fraction of vehicles would be equipped to transmit their origins, destinations, and locations en route. These data could be used to enhance the historical data for forecasting travel demand in the next time interval and to obtain route travel time information from actual vehicles moving through the street network. If the technology for receiving transmissions from many vehicles were feasible to implement, then the number of vehicles with transmitters would gradually expand. At this stage a capability to allocate vehicles to multiple routes between specific origins and destinations might be necessary in order to achieve a user-optimal equilibrium.

The third generation system could implement the potentially more efficient system-optimal equilibrium. This system would require that most vehicles be able to transmit and receive information. It might also require implementation of a toll system to provide incentives for use of the system-optimal routes.

Secondary benefits of all three generations would be enhanced information on O–D travel times by automobile. These times could be displayed on a cable television channel or obtained from a dial-up service, and used to improve traveller's decisions regarding departure time, mode, and location of residence and workplace, as discussed above.

FUTURE PROSPECTS

The design, testing, and implementation of the route guidance system described in this paper seems unlikely to progress beyond the navigator systems now available unless a compelling case can be made in terms of the system's benefits and feasibility. A number of basic questions concerning the system have been identified in the paper, including the following:

1. What are the likely savings in travel time from user-optimal route choices as compared with existing dispersed route choices?
2. What additional savings would result from the introduction of system-optimal route choices and the timing of traffic signal systems with better historical and real time information?
3. How would improved highway travel time information change the behavior of commuters with regard to departure time, choice of mode, and choice of residential or job location? What would be the benefits or costs of these changes?

In addition, a number of more technical questions need to be addressed, including the following:

1. Can the existing static network equilibrium models be adapted to a quasi-dynamic formulation suitable for analyzing shorter time periods?
2. Can the communications problems inherent in the system described be solved in a cost-effective manner? What would be an optimal communication system design?
3. Is the traffic flow information obtained from traffic flow measurement equipment presently available or under development adequate for determining route travel times? If not, what improvements would be necessary to make it adequate?

The implementation of an urban route guidance system would likely be the most important advance

in urban transportation since the construction of urban freeway systems in many developed countries in the 1950–1980 period. It would combine major technological advances in communication, computers, and transportation to produce a truly high-technology urban transportation system which could substantially enhance the quality of life of the working population in large urban centers throughout developed countries of the world. While it may not address more fundamental problems of health, education, and the general welfare of the population, this system could release other resources including time, the scarcest resource of all, to improve these conditions as well.

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