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THE MODELLING OF DYNAMIC ROUTE GUIDANCE SYSTEMS

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The modelling of dynamic route guidance systems

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Abstract

In attempting to simulate the operation of a dynamic route guidance system, the modelling task is concerned both with the operation of the control system and with the implications this has for modelling driver behaviour (whether or not the driver is receiving information from the controller) and network conditions. The aim of this paper is to provide an overview of the modelling issues which need to be considered when addressing such a problem, and which have been identified by various authors in reports on experimental/survey work and in discussion papers.

In discussing the great number of challenges to the modelling world which have arisen from the interest in such systems, we seek to stimulate further discussion and to provide a framework within which any route guidance model may be critically evaluated. We consider such a framework to be particularly timely in the light of the wealth of simulation models currently being proposed - and widely varying conclusions being drawn - as a result of many major research initiatives currently underway throughout the developed world.

It is our belief that the development of a model which adequately represents the performance of a dynamic route guidance system is of the utmost importance to the success of such an approach. It will not only provide a means for evaluating the potential benefits, but should also provide an essential insight into the most appropriate means for its implementation and improve our understanding of transportation networks.

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1. INTRODUCTION

The age of information technology is upon us. Whilst there is - perhaps rightly - some scepticism regarding the effectiveness and financial feasibility of such techniques when applied to transportation, it will only be a matter of time before central and local governments are lured by the potential for a reduction in congestion, harmful emissions and accidents, and the promise of an improved Quality of Life.

Indeed, many cities already benefit from sophisticated traffic signal control techniques (such as SCOOT - Bretherton & Bowen, 1990) and, to a much lesser extent, variable message signs. This paper is concerned, however, with a type of control with which there has been virtually no experience (with Berlin currently having the only fully operational system - see Von Tomkewitsch, 1987), but which has caught the imagination of those involved in a number of major projects throughout the world - notably, the EC's DRIVE initiative (Stergiou & Stathopoulos, 1989; Keen et al., 1991); in the USA, the IVHS steering committee (IVHS America, 1991), as well as, for example, the Minnesota Guidestar programme (Ofstead, 1991), Orlando's Travtek project (Rillings, 1991) and the Chicago dynamic route guidance system (Boyce et al., 1991a); and studies with a number of systems in Japan (summarised by Yumoto, 1991) such as the Comprehensive Automobile Control System (Kobayashi, 1979) and the Advanced Mobile Traffic Information and Communication System (Tsuzawa & Okamoto, 1989).

Before proceeding, we should define what we mean by the terms we will use. In this paper, by the term 'route guidance', we shall usually be referring to a system - applied over an urban area - in which individual vehicles are equipped with devices which communicate information on the 'best' route for that particular vehicle's (user-requested) movement. On the one hand, there is *static* route guidance, which recommends routes on average or expected conditions; although it may recommend different routes at different times of day, it does not respond to traffic conditions actually experienced at that time. On the other hand, in this paper we shall be concerned only with *dynamic* route guidance (DRG), which bases route recommendations on actual or predicted traffic conditions using data from various detectors in the network, with the recommendations being frequently updated (say, for example, every five minutes). These are the basic principles behind DRG; we shall discuss the details of how this is achieved further on in the paper, as these are relevant to the modelling process. In fact, we shall deliberately treat the term 'route guidance' ambiguously, so that we also include in our modelling discussion 'information systems' which provide information to the driver on current or predicted traffic conditions, without recommending a route to follow.

In terms of tackling the problem of urban congestion, DRG systems have the advantage over alternative methods of control mentioned earlier (linked, vehicle-actuated traffic signals or a system of dynamically updated variable message signs) in that they provide the opportunity to influence individual drivers, depending on their own origin and destination and possibly their own route selection criterion. By coordinating the dissemination of the guidance information, such systems are consistent with the current network-wide methods for assessing traditional traffic management measures, in the sense that the control system can help to ensure, to some extent, that any local congestion problem is not simply shifted to another part of the network. The other main advantage of such systems is the possibility for equipped drivers to generate the data on which their routing information is based (through two-way communication links).

On the other hand, DRG has a number of disadvantages over the alternatives (particularly variable message signs). Firstly, unless the use of in-vehicle guidance systems is ultimately made compulsory, there is the potential to influence the behaviour of only a proportion of the driver population (say, at most 20%-30%). Furthermore, DRG is a much more expensive option for traffic authorities who have to buy and install the infrastructure (and indeed for drivers, who have to pay for the in-vehicle device). It follows, then, that it is crucial to have a reliable model of such a system, in order to have a prior indication of the likely benefits of such a large investment, as well as to determine the best strategy for implementation.

Clearly, *routes* followed in a network are a key part of any DRG model. The theory of equilibrium assignment - though a crude model of driver route choice - has been established for over two decades. On the other hand, practical - yet sophisticated - computer models of route choice behaviour (such as CONTRAM (Taylor, 1990), SATURN (Van Vliet, 1982) and TRIPS (MVA Sytematica, 1987)) have been used for many years to evaluate the impact of traffic management schemes. One would have thought, then, that the development of a computer model of DRG based on sound theoretical principles would not have been too onerous a task. It is now clear that this problem has in fact been one of the greatest challenges laid down to transport modellers in recent times. Indeed, as Smith and Ghali (1991) commented, technological developments are taking place at a much greater rate than improvements in the understanding and computer modelling of networks, with the result that 'there is a substantial risk that technological "solutions" to urban congestion will be designed with an inadequate theoretical background, and imposed on real-life networks with no proper evaluation'. Even the development of a computer model based on sensible, though not necessarily theoretically founded, principles is no trivial task, and there is certainly no consensus on how the problem should be approached. It is noted at this point that in the discussion to follow, it will often be convenient to illustrate the modelling requirements by relating them to the deficiencies of conventional static equilibrium models, since these are really the only established methods of representing routing behaviour in a network.

The aim of this paper is to identify the issues involved in developing a model of DRG. In order to achieve this, we will draw on the reported findings of a number of computer-based laboratory experiments, attitudinal and behavioural surveys and simulated route guidance systems, as well as the opinions expressed in discussion papers on this subject.

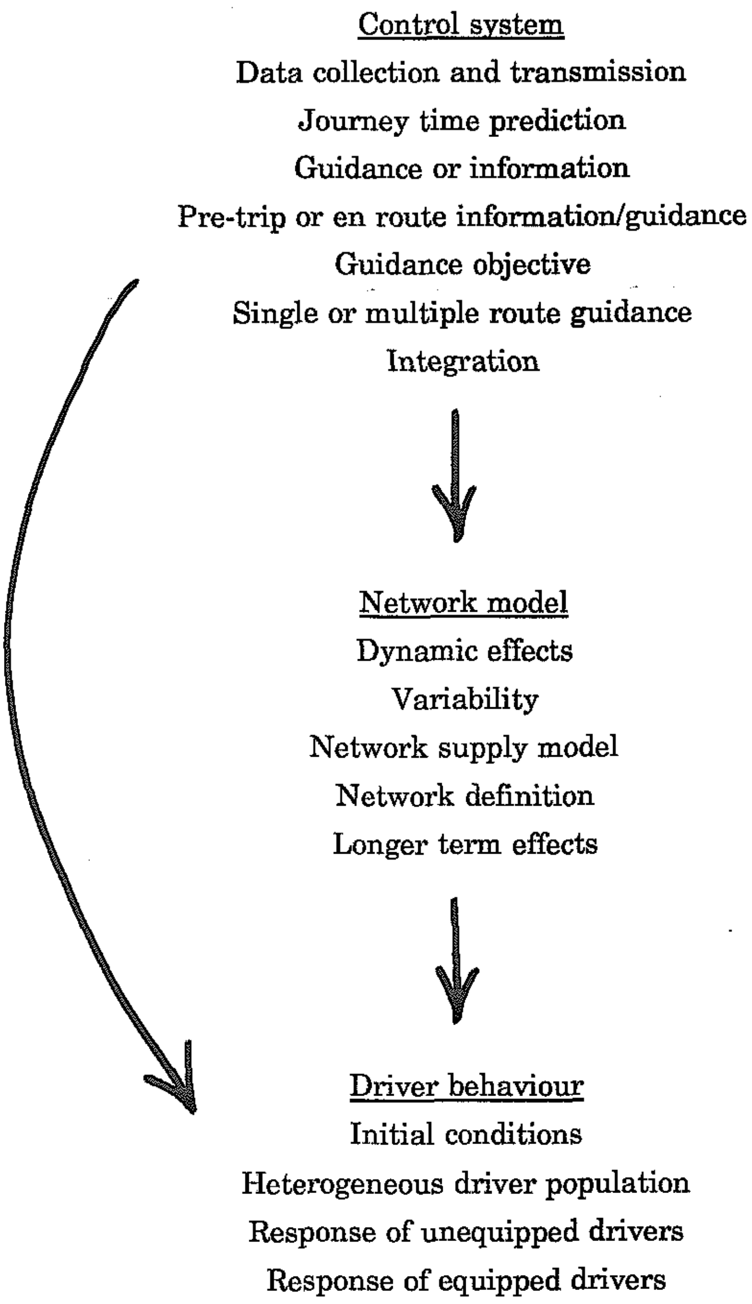
We note at this stage that it is not intended to comment on the general issues of network modelling, even without guidance in operation; we only deal with those aspects arising specifically from the route guidance problem. Likewise, we do not intend to carry out a review of past attempts at route guidance modelling - the reader is referred to Van Vuren & Watling (1991) - and only cite the results of such work when they have direct relevance to the modelling task.

We hope that the discussion to follow may serve to involve more people in the debate over what is the 'correct' approach to modelling DRG. Furthemore, it is unlikely that a model will ever exist which takes account of *all* of the factors described. It is important, then, when interpreting the output of any model, to take into account assumptions made and features *not* modelled; hopefully, this paper will also prove to be useful as a 'checklist' in such a situation.

We will aim to consider each of the modelling issues separately (without trying to infer any order of importance), although there is clearly a good deal of overlap and interaction between the different aspects discussed. They may be grouped into three broad categories, which we shall call: 'control system', 'network model' and 'driver behaviour'. The control system category is concerned with the dissemination of information/guidance, data transmission and computation, and (in the case of guidance) the criteria from which the routing advice is determined. The network model category is concerned with the definition of the network available to users and the control system, and the underlying dynamics, random variation and long term changes in network supply and origin-destination travel demand conditions. Finally, the driver behaviour category relates to factors which influence - and rules which determine - the response of drivers to network conditions and (in the case of equipped drivers) to the control system.

The areas which will be addressed in each of these three categories are summarised in the figure below. The arrows are intended to signify the way in which the modelling of one component determines, to some extent, the modelling requirements for another. The approach we shall adopt, then, is firstly to consider the control system independently of the other two categories, identifying the variety of such systems which may need to be considered and the modelling implications of each. Secondly, given this discussion, we examine to what extent the simulation of the control system affects the choice of network model. Finally, taking into account the framework suggested by the needs of the control system and network model, we propose some possible bases for the representation of driver behaviour.

It could reasonably be argued that there should also be a feedback, say, from the requirements for modelling driver behaviour to those for the control system; the justification for the approach we have adopted is the belief that it is the *control system* (namely, DRG) which has caused modellers to question the suitability of current simulators, and so this must be the driving force behind any new approach. We also note that it is our aim to provide a *discussion* rather than a model specification; in the latter case, since compromises invariably need to be made, such a feedback would of course be important.



Control system
Data collection and transmission
Journey time prediction
Guidance or information
Pre-trip or en route information/guidance
Guidance objective
Single or multiple route guidance
Integration

Network model
Dynamic effects
Variability
Network supply model
Network definition
Longer term effects

Driver behaviour
Initial conditions
Heterogeneous driver population
Response of unequipped drivers
Response of equipped drivers

2. CONTROL SYSTEM

2.1 Data collection and transmission

We shall begin with what is the technological basis of a DRG system; that is, the ability to monitor traffic conditions, to communicate this information to some (central) data processing device and thence to transmit recommendations to equipped drivers (Thomas, 1990; Catling & Bell, 1990; Dehoux & Toint, 1991). The modelling implications of this aspect of the control system may be classified as 'uncertainty', 'time lags' and 'diversity'.

Firstly, uncertainty in the data arises from the reliability of the detectors (that is, the devices which collect data on prevailing conditions) and due to transmission faults in relaying this information to the data processing centre.

Secondly, time lags occur between the period over which traffic conditions are measured and the instant at which a response is elicited from a driver equipped with a DRG device. These lags will be a function of the response time of the detectors and of the limitation on data transmission rates imposed by the communications system, as well as the time taken to compute recommended routes.

Thirdly, any general purpose DRG model must be able to accommodate a diversity of systems (with varying attributes) which may need to be evaluated, as well as different types of equipment used within a given network (Dehoux & Toint, 1991). For example, traffic conditions may be monitored using inductive loop detectors and/or using feedback from two-way communication links with those equipped with route guidance devices; looking to the future, it may prove feasible to use information on congestion patterns automatically extracted from video surveillance (such as the incident detection techniques of Rourke et al., 1990). These methods will estimate different traffic characteristics (eg journey times, traffic volumes, average speeds), will have varying response times, will have different reliabilities and will work to different levels of precision (for example, loop detectors aim to monitor *all* vehicles passing, whereas the two-way communication links can track only the subset of drivers who are equipped). On the other hand, a general purpose model may be required to represent the delays, capacities and reliabilities of different communications media; there appears, as yet, to be no consensus on the most appropriate means (for example, the German LISB system (Von Tomkewitsch, 1987) uses infrared, the Japanese RACS (Takada et al., 1989) uses radio beacons, AMTICS (Tsuzawa

& Okamoto, 1989) makes use of cellular radio and the Pathfinder project (Mammano & Sumner, 1989) uses radio broadcasts to transmit information).

Throughout this paper, there will tend to be the implicit assumption (unless stated otherwise) that all data are sent to a single, central control system, covering the urban area of interest. Now, on the one hand, it may be desirable to have data - and provide information/guidance - relating to a much larger area (at one extreme, it has been suggested that pan-European centres may exist - Thomas, 1990). While this data may be somewhat different to that available for the main central area - being coarser and perhaps based on expected rather than prevailing conditions - one would expect that the same general model of the data communications system would be applicable. Some modification may be required, however, towards the other extreme, when the data for the urban area are handled by a number of local devices, these devices being able to communicate with one another in some restricted way. Yumoto (1991) suggests such a 'horizontal configuration', in which detailed data is only available near to a local device, 'historic' data (updated less frequently) being used for more distant parts of the network.

When developing a model of DRG, compromises will undoubtedly need to be made; whilst the collection and transmission of data is in some sense the basis of the system, many may consider it to be one of the first features to consider neglecting. We have discussed in this section the variety of hardware which may be used, some probably more appropriate for particular circumstances/networks; it should therefore be borne in mind that it may well be a requirement of a DRG model to at least obtain a first approximation to the relative effectiveness of different data systems.

2.2 Journey time prediction

The ability to estimate journey times using data relayed from roadside detectors is likely to be at the heart of any (prescriptive) dynamic route guidance system. Whilst one could imagine other descriptors to be of use in a pure (descriptive) information system, the ability to recommend routes must be based, at least partially, on journey time considerations. In this section, we consider issues relating to this problem, including forecasting, combining estimates and sampling variability. We will relate the discussion in the main to 'two-way' systems, which collect data from - as well as relaying information to - equipped vehicles; many of the issues are, however, relevant to other sorts of system discussed in section 2.1.

Now, on the one hand, given suitably positioned detectors, a sufficient number of vehicles passing them and a means for 'tracking' vehicles (eg by an equipped vehicle transmitting to a detector the identity and time of the last detectors it passed), one may think that this estimation problem is relatively straightforward: route recommendations may simply be based on *current* (mean) journey times. There is no guarantee, however, that such an approach will be effective (although there may be some justification in using it if traffic conditions are quite stable), because traffic conditions may change considerably in the time taken for the data to be relayed from the detectors to the control system, the routes to be calculated, the information to be sent to drivers and the drivers to actually use a route. This calls, then, for an anticipation of future events: a daunting task, as they are a function of the capabilities of the system architecture (see section 2.1), of the routes recommended, of driver response to the recommendations, and of other, unknown factors.

Taken to an extreme, one could imagine the journey time estimation and computation of recommended routes being adapted by combining them in an iterative loop with a full simulation of the evolution of the network from the currently estimated conditions, before recommendations were actually sent out to equipped drivers (an approach similar to this was investigated by Van Vuren and Watling (1991) in the context of static route guidance to multiple routes). Calculating dynamic journey time estimates rapidly in an on-line system, on the other hand, may not be feasible; in any case, there has to be some trade-off between the computation time taken by the control system and the fact that the data on which it is based is becoming out of date. It will therefore be necessary to resort to approximate methods.

In the case of recurrent, dynamic congestion - such as in the build up and decline of a peak period - it would be possible to use 'historic' information on the evolution of travel times within a day and on the location of economic activities (Kitamura & Jovanis, 1991; Marchent, 1989). Such information could be used to forecast expected temporal changes from the current journey times; by the same token, if the current journey times fall outside typical limits then they may be indicative of an unexpected 'incident'. One could then envisage the frequency at which the control system requests data from the detectors to vary spatially, dependent more on 'event-based' considerations than a fixed time slice.

Whatever journey time prediction model is used there is likely to be the necessity to combine historic data (probably gained by monitoring equipped drivers on previous days) with current/predicted estimates. On the one hand, the historic information is based on a large amount of data and so would be expected to predict recurring patterns with a good deal of precision, but is insensitive to current conditions. The 'real time' estimates, on the other hand, are based on a much smaller sample size (and for some parts of the network, there may be no equipped vehicles from which to obtain up to date information). Care has to be taken, then, in constructing sound statistical methods with which to combine these data sources. Furthermore, difficulties are inherent in simple smoothing methods typically used in traffic surveillance techniques, which aim to predict traffic conditions for one time slice ahead (Kitamura & Jovanis, 1991). On the one hand, if only a small 'weight' is given in the prediction to deviations of current traffic conditions from the expected, then the control system will be slow to respond to incidents. This is because on the other hand, giving a large weight to such deviations means that there will be a response by the guidance system to every small variation in the network conditions - the undesirability of the instability in traffic conditions which may arise as a result of such guidance is discussed elsewhere (section 2.6).

There are a number of other aspects of which the route guidance model as a whole may need to take account, mainly related to the precision of the journey time estimates.

Firstly, with equipped drivers essentially acting as the 'sample' from which these estimates are (partially) formed, one would expect an increase in precision as the number of equipped vehicles increases. Gordon (1989) has also noted this point, and suggested delay at traffic signals to be the predominant cause for travel time variability; based on this assumption, he succeeded in building a relationship between the estimation error at a given intersection and the percentage of vehicles equipped.

Secondly, the number of equipped vehicles will affect the 'coverage' of the network - that is, the parts of the network in which real-time information (even from a single vehicle) is available (Boyce et al., 1991b).

Thirdly, the density and location of the detectors (for example, whether they are only on major roads and the distance between them) may give rise to spatial differences in the precision of the journey time estimates and in the speed of response to unexpected circumstances.

Finally, there may also be the problem of combining or of giving priority to on-line data from different sources: for example, they may have different accuracies, some may be based on equipped drivers and some on all drivers, and they are likely to be at different locations.

2.3 Guidance or information system

Having considered the monitoring of traffic conditions and the subsequent formation of travel time predictions, the following four sections are concerned with the use to which this information is put.

We attempt to cover in this paper both guidance systems (which are 'prescriptive', in that they advise routes without giving information on prevailing traffic conditions) and information systems (which are 'descriptive', providing information on conditions only, with no routing advice). Since many of the issues raised in this paper are either applicable to both systems or are clearly only relevant to guidance systems, then we have not in the main sought to distinguish the two. In this section, we seek to appease those reading this paper who believe that a clear distinction between the issues relating to each system should always be made, by discussing areas in which the modelling task may differ.

Aside from the obvious point of the different types of data collected and transmitted, the differences between a suitable model of guidance and one of an information system are likely to be primarily in the response of equipped drivers. One aspect is the frequency of consultation of the on-board equipment (Mahmassani & Chen, 1991). On the one hand, an information system provides a general picture of the state of the network, leaving the driver the task of determining a suitable route in his own mind; having decided on a route, one may expect him periodically to check for unexpected conditions. On the other hand, a system which recommends a route to follow may be consulted much more frequently, particularly in unfamiliar areas; the driver is likely to become reliant on the system to advise him of the necessary turning movements at the appropriate time. The implication is that during a driver's trip, he may re-assess his original choice of route more frequently when equipped with a dynamic route guidance device than when following a dynamic information system; in other words, models should recognise that the decision-making process may be 'more dynamic' in the former case.

There is also evidence to suggest that different types of information are likely to elicit different responses according to the characteristics of the driver (with the implication that the guidance control system may have to target groups of drivers with particular types of advice - Barfield et al., 1989). A number of possible criteria have been suggested for dividing the driver population according to their response to various types of information. These include classifying drivers according to their familiarity with the network, with evidence to suggest that regular users prefer information alone, whilst those in unfamiliar areas have a preference instead for guidance (Bonsall & Parry, 1990); or grouping them according to general navigational ability (Gould, 1989).

In addition to systems which provide each driver with *either* guidance or with information, it may be appropriate to examine control systems which supply *both*. It has been suggested that the credibility of a guidance system (and hence the compliance* with the recommendations) would be improved by the addition of congestion information (Kitamura & Jovanis, 1991; Bonsall, 1991). On the other hand, evidence from a human factors' simulation experiment suggests that whilst this may be the case, a combined guidance and information system only elicits a slightly greater response than pure guidance (Allen et al., 1991). This is clearly a question of some interest, suggesting that it would desirable for the model to be sensitive to the type of and amount of information provided.

With regard to the experiment of Allen et al. above - which tested four types of in-vehicle system (static information, dynamic information, dynamic guidance, dynamic guidance plus information) when responding to freeway incidents - it is interesting to note that in terms of influencing drivers to divert, the four systems performed quite differently. Also, there was evidence that the systems varied in terms of the delay before drivers decided to divert.

The implication of this section is that a model which claims to be able to simulate different types of advice system should recognise a link between the type and amount of advice given, the characteristics of the driver, the dynamics of the decision-making process and the response to the information provided.

[* It is noted that some care has to be taken in the interpretation of the term 'compliance' - it often refers to the percentage of equipped drivers who used the same route as that recommended. Often, the term is used in experiments or surveys where the route which a driver was intending to take without guidance is unknown; in such cases, we do not know that the driver is complying with the information: he may have chosen that route anyway.]

2.4 Pre-trip or en route information and guidance

Whether the driver receives information or guidance, in-vehicle dynamic advice systems have the potential to influence a driver's route choice at different stages of his trip; so, for example, during the journey the control system may advise the driver to divert from the route originally recommended, in the light of unexpected conditions in the network. Pre-trip systems, on the other hand, may only affect the decision process at the origin of the trip. In the former case, there is a clear need to move away from the assumptions of established route choice models, towards dynamic models of the decision process. Furthermore, since en route choices are probably made with less time to assimilate the advice given than pre-trip systems, they may be somewhat less effective (Stephens, 1990).

A comparison of the two types of system is clearly an interesting topic - since pre-trip information could be supplied at the home or office, requiring considerably less investment in infrastructure. It is worth noting that with such a motivation, some preliminary comparisons have been carried out with pre-trip and en route (descriptive) information (Mahmassani & Chen, 1991), with the conclusion that the relative benefits depend greatly on the conditions in the network before the information system was in operation, as well as the assumed response of drivers to the information.

Two points should be noted in modelling the response of equipped drivers to en route guidance. Firstly, experiments suggest that acceptance of advice is decided on a junction-by-junction basis (Bonsall et al., 1991); so, for example, the fact that a driver follows a recommended route at one junction does not mean that he will follow it at the next, although one would expect there to be some correlation. Secondly, the analysis of data from one motorist survey (Haselkorn et al., 1989) was able to identify four major types of driver (approximately in the ratios 1:1:2:1 respectively): 'route changers', for whom both pre-trip and en route information often affects their route choice, although the former does not cause them to change mode or departure time; 'non changers', who rarely change any aspect of their journey in response to information; 'route and time changers', who are sometimes influenced by en route information, and who often change their departure time or pre-trip route choice; and 'pre-trip changers', who rarely take notice of en route information, but may change their pre-trip route choice, departure time or even mode. It would seem desirable, then, for any model to be able to accommodate groups of drivers with different responses to pre-trip and en route information/guidance.

2.5 Guidance objective

In the following two sections, we shall restrict attention to two features specific to prescriptive DRG systems.

A research study (Marchent, 1989) concluded that if vehicle route guidance is to achieve wide acceptance, then 'it should be provided as a public service or private operation funded by users' licence fees'. In this paper we approach the problem from the viewpoint that - at least for the foreseeable future - systems will fall into the latter (voluntary purchase) category. In spite of the current trend in consumers being willing to pay more for products which cause less damage to the environment, but which may be less effective than their previous choice, it seems unlikely that drivers will choose to make the investment in a route guidance device without the expectation that it will improve the efficiency of their own journeys. The local authorities, on the other hand, are likely to be more interested in the benefits to the community as a whole; in particular, the minimisation of *total* travel time - this objective is quite different from the user optimal one. The problem in using such a system optimising strategy is that a number of drivers will be recommended routes which are longer than their own personal minimum time route (or even the route they would have chosen without guidance in operation); if drivers perceive a substantial difference, they may not be willing to accept such a penalty. It follows that a fruitful line of research may be to study strategies which are closer to minimising total travel time than a 'user optimal' strategy, but which are constrained so that the penalty to equipped drivers may not exceed a given percentage (a strategy suggested also by Mahmassani & Jayakrishnan, 1990).

The implication of the above is, however, that when modelling strategies which are not user optimal, the behaviourial rules should recognise a dependence of a driver's response to guidance information on its (perceived) benefit to the user. This is therefore also the case for strategies whose objective includes a safety factor (Gillan, 1990; Wackrill, 1990), which could mean lower speed roads, less opposed turning movements or a reduction in risk to pedestrians (by discouraging the use of residential roads, for example). The guidance objective may also take account of environmental factors, such as pollution (as in the CACS system mentioned earlier) and fuel consumption (Stergiou & Stathopoulos, 1989). In view of this problem of encouraging compliance with guidance advice which is not optimal for the user, some advocate the use of a road pricing scheme to resolve the conflict of interest (see also section 2.7).

We have discussed above the problems of whether to optimize with respect to the user or the system, and what measure (travel time, fuel consumption, ...) to use in the objective. The final issue to decide is whether the control system is a 'local' or centralised one. So far, we have tended to make the implicit assumption that a centralised system would be used; indeed, simulation studies have indicated that co-ordination in the information provided will be essential at some level of market penetration (Mahmassani & Chen, 1991). However, it is recognised that a number of decentralised strategies exist which may also be effective - for example, a strategy has been investigated which adjusts route recommendations in response to local 'perturbations' in traffic conditions (Mauro, 1991). This strategy is also distinctive in that it has no specific optimization objective; it aims instead to keep traffic conditions as close as possible to some controller-specified predetermined flow pattern.

Indeed, a further possibility which could be modelled is that instead of continually updating recommendations in real time, the control strategy has a number of 'plans' from which to choose depending on whether certain indicators of network conditions fall within specified limits. Alternatively, the control system could have 'standard' sets of route recommendations it uses for different times of day and different days of the week (updated occasionally in the longer term, to allow for seasonal effects), and will only switch to a real-time system when a significant disruption in the traffic pattern is detected. (These are something akin to strategies suggested by Boyce, 1988). These types of strategy both have the advantage of requiring less computing effort and transmissions, and give some consistency in the information between different days; their effects may also prove rather easier to model and predict.

2.6 Single route or multiple route guidance

As the number of unequipped drivers increases, there will be some point at which recommending the same route in a particular time slice will cause a sufficient number of drivers to divert, that the recommended route itself becomes congested. In fact, it may even transpire that the network conditions as a whole deteriorate relative to the situation before guidance was in operation (Breheret et al., 1990). An obvious response is to increase the rate at which route recommendations are updated, but there are a number of difficulties with such an approach. Firstly, there are limitations on the update time, imposed by the time taken to relay data from detectors, compute route recommendations and transmit them to drivers; whilst this will be dependent on the system architecture

, it is quite possible that market penetration will reach such a level that these limits are reached. Secondly, with recommended routes updated very frequently, the journey time prediction will be based on very small 'sample sizes' - that is, on a small number of trips per update period - with a corresponding loss of precision in the estimators (journey time prediction is discussed at greater length in section 2.2). Furthermore, in such a situation, the workload for the control system would be great. Thirdly, rapidly updated recommendations are likely to result in instabilities; for example, a situation could be envisaged in which two competing routes with similar attributes are alternately recommended in successive time slices. Such instability is likely to make it extremely difficult to co-ordinate traffic signal settings (CAR-GOES, 1990). One would also wonder whether the credibility of the guidance system would be brought into doubt in such a situation: towards the end of a time slice, congestion may be visible on the recommended route, meaning that the driver is less likely to comply with the guidance advice (Bonsall et al., 1991). Whilst it could be argued that driver behaviour then essentially solves the problem (in a similar vein to which urban congestion is said to be a form of demand management), it is likely to have the result that the driver is less willing to follow guidance in the future, as he has perceived it as giving poor advice previously.

If a route guidance model is to be used to assess future scenarios with a significant proportion of drivers equipped, it would seem necessary for it to represent control strategies which divide the guided traffic between a number of different routes (per origin-destination movement), independently of the objective upon which the guidance is based. One possibility would be to divide traffic according to some probabilistic (eg logit, probit) rule, depending on the current estimates of route journey times. However, a more appealing (and more equitable) way of achieving multi-routing seems to be to allocate drivers making a particular movement in such a way that they are on multiple, equal time routes (Yumoto, 1991; Boyce, 1988; Van Vuren & Watling, 1991) - by taking account of (dynamic) estimates of relationships between travel time and flow, in a similar vein to equilibrium models. In this way, it is possible to anticipate the effect of re-routed traffic on travel times, whilst taking account of the different attributes of the routes (eg capacities). In a practical situation, the multiple optimal routes determined could then be allocated to the appropriate drivers at random - either by the central control unit or (approximately) by some form of 'sampling' by the in-vehicle device (Yumoto, 1991).

2.7 Integration

Whilst the implementation of a route guidance system alone is hoped to give rise to significant benefits, it may well be that the true worth of such a system is not realised until it is integrated with other techniques of traffic management, control and information. The ability of a route guidance model to represent the interaction with other systems should therefore be borne in mind.

It is only natural to consider an integration of route guidance with traffic signal control. Much of the existing infrastructure of the signal control system (detectors, communications links) can be of use for a route guidance system, too, whilst there will be a benefit in the sharing of the similar sorts of traffic data (link speeds, queues) that both systems need (Catling & Bell, 1990). More importantly, there exists a logical *need* for such an integration, as traffic signal settings should be based on (historic or real-time) flow patterns, which will be strongly determined by the route guidance system, whilst the guidance control system itself will need up-to-date signal information to be able to advise optimum routes over the network. Proper integration would take the interaction between signal timings and route choice into account, so as to pursue the objectives of the system manager, whilst accepting possible conflicts with drivers' selfish behaviour. These objectives could be an overall reduction in network travel times, or a desire for localised re-routings away from environmentally or safety sensitive areas. Here we move into the domain of network design, although in the case of route guidance we have (at least partial) control over the routing of equipped drivers. We note in passing that the potential for overall travel time savings by integrating route guidance and traffic signal control has been researched by Smith and Ghali (1991) and Van Vuren et al. (1990); estimated extra benefits are at least equal to those from improved route information alone.

The integration of a route guidance system and an electronic road pricing scheme offers a number of distinct advantages (Catling & Bell, 1990; Brett & Estlea, 1989). On the one hand, the sharing of the physical infrastructure may make it financially appealing; in terms of modelling this may mean that an allowance has to be made for the extra communications burden. Secondly, in the medium term, road pricing offers a means for controlling the release of suppressed demand, which may arise in the longer term following the introduction of a DRG system (discussed in section 3.5). Thirdly, pricing could be used to encourage equipped drivers to comply with - for example - system optimal guidance or guidance reflecting environmental goals, which it may not otherwise be in their best interest to follow. Finally, a combined pricing/guidance system is likely to make the pricing system more effective (assuming that the aim of the pricing scheme is to reduce congestion or environmental damage, rather than to raise revenue), by encouraging the use of areas which have a low toll - the guidance system gives the means to plan alternative routes which avoid tolls.

Whilst integration of route guidance systems with other sources of congestion information and guidance - such as home-based pre-trip systems and variable message signs - may give rise to a benefit due to the increased exchange of data, a more important effect may be the increased credibility of both systems. Such integration should give the means for avoiding situations in which - say - the next turning movement of an equipped driver's recommended route is to the left, but a variable message sign indicates turning right for the same destination. It should be pointed out, however, that results reported from simulated experiments of such a conflicting situation - though, perhaps importantly, with fixed rather than variable, congestion-responsive signposts - appear to show that compliance with (user optimal) guidance is not much affected for that particular decision by such conflicting information (Bonsall et al., 1991). Nevertheless, it could be the case that the long-term credibility of the system is damaged.

It may also be desirable to consider the modelling implications (for example, the effect on trip distribution and mode choice) of route guidance systems integrated with parking guidance (Hilton, 1989) or schemes giving priority to public transport.

3. NETWORK MODEL

In 1952, Wardrop proposed a model of route choice behaviour which forms the basis of many of the computer models of network performance used today to assess the impact of traffic planning and management measures. It is assumed that an homogenous population of time (or, more generally, 'cost') minimising drivers exist on the network; that the origin-destination demand for travel and the network ('supply') conditions are static - that is, they do not vary with time over the study period - and are inelastic; that we wish to examine a single 'steady state' of the system, which prevails after the same static conditions have occurred for some long period of time; and that, during this period of repeated static conditions, drivers have experimented with different routes when repeating their 'origin to destination' movement, to such an extent that they are certain about demand and network conditions. This is the so-called 'user equilibrium' assignment model.

In some respects, this general approach is emminently suitable for modelling DRG, primarily because of the way in which it is able to handle the interaction between network supply and travel demand (see 3.3). However, the specifics of the assumptions of the user equilibrium model (even though it is possible to relax some of them - see Van Vuren & Watling, 1991) mean that it has a number of serious deficiencies in the context of DRG. By using this model as a baseline, sections 3 and 4 of this paper aim to discuss new modelling requirements brought about by the consideration of DRG systems.

In this section, we shall mainly discuss issues relevant to the representation of origin-destination demand for travel and network supply conditions. These issues have been identified by considering the overall aims of the control system (see sections 1 and 3.4) and the configuration and model of the control system (section 2). Deviating slightly from the structure of the paper proposed in the Introduction, we shall also on occasion look forward to section 4, since the type of driver response which the DRG system hopes to elicit is also of relevance to the model of supply/demand.

3.1 Dynamic effects

Static models - such as the equilibrium one mentioned above - have the obvious deficiency in the context of simulating DRG, that they are unable to represent time-varying effects of the study period. (We note at this stage that we will be dealing in this subsection only with 'within day' dynamics; issues such as daily variations in conditions or trip-to-trip 'learning' adjustments in driver route choice are dealt with elsewhere - in particular, see sections 3.2 and 4.4). In the past, this has probably not been a great problem, when the use of such models was to evaluate traditional (fixed) traffic management measures, such as one-way systems or junction modifications. In such cases, the fact that in reality, for a short time during the peak period (say), a significantly greater than average number of trips making a given movement causes a particular intersection to work somewhat inefficiently; this may be acceptable, provided that the performance on the whole is good over the peak period. Dynamic route guidance, on the other hand, is geared to a rapid response to short-term changes in traffic conditions; furthermore, in order properly to evaluate the performance of the control system, there is the need to represent delays between prevailing traffic conditions being monitored and drivers being recommended routes / actually traversing the network. In this section, we will aim to identify the important dynamic effects, and the underlying processes of network supply and origin-destination demand which need to be modelled in order to reproduce these effects.

In terms of routing behaviour (that is, the route choice of equipped and unequipped drivers, as well as the recommendations provided), perhaps the most important aspect to represent is the fact that the attractiveness of competing routes may vary during the study period, primarily due to the variation in time of origin-destination demand. Thus, for example, the optimal route - according to a particular driver's criteria, or those of the control system - during one five minute time slice may no longer be optimal for the subsequent five minutes. We will satisfy ourselves here with identifying the *need* for a time-varying origin-destination demand matrix, without touching on the difficult - but separate - problem of how to estimate it. It is noted, however, that the level of dynamic resolution deemed acceptable for the demand matrix (that is, the length of the time slices over which it is assumed to be constant) may be influenced by the need to determine the effect of time lags in the control system (section 2.1) of the order of perhaps five or ten minutes.

A second problem with static equilibrium models in this context is the fact that the demand is assumed to be instantaneously propagated across the network; there is no representation of moving in space and time through the network. When evaluating DRG systems, there are many spatial/temporal factors to assess, such as the location and update frequency of the detectors and the roadside devices which communicate route recommendations, as well as the forecasting power of the journey time prediction algorithm. When assigning the demand to the network, then, it is important to take proper account of effects such as time-dependent queuing; the model of network supply conditions is discussed at greater length in section 3.3.

Thirdly, given the form of time-varying model described above, it is possible to take account of the dynamic nature of a driver's decision-making process during his trip. This factor assumes particularly great importance when there is a need to simulate driver response to incidents (see 3.2, 4.4) and the effect of DRG on this behaviour.

We mention finally in passing that the need to represent the effect of time-varying demand and queuing has already prompted a great deal of effort in developing a dynamic extension of Wardrop's equilibrium (for example: Friesz et al., 1989; Smith & Ghali, 1990; Janson, 1991; Papageorgiou, 1991). At present the problem is unsolved for general transportation networks; indeed, there is not even a consensus over what the dynamic extension should be.

3.2 Variability

Although the models of dynamic equilibrium assignment mentioned above have differences in the way in which they handle dynamics, they are unified by the fact that they are aiming to model the long-term average behaviour of drivers (in terms of route choice and possibly also departure time) who have had sufficient previous experience of the same dynamic network conditions to achieve an equilibrium. In particular, then, they are only suitable for representing recurrent congestion under the same daily conditions; they are unable to take account either of day-to-day variability or of incident-induced congestion. (In other words, it is the *equilibrium* concept which is in question - see also Dehoux and Toint, 1991, for a lucid discussion of this issue).

When assessing traditional traffic management measures, it could again be argued (see also 3.1) that it has been reasonable to base the evaluation on average daily conditions (although there is some argument for performing sensitivity testing - Mutale, 1991). Dynamic route guidance, however, must be able to respond to variations in origin-destination demand between different days in the same week and between different weeks, and as with the dynamic effects discussed above, the model must be able to simulate the effect this has on the behaviour of drivers with and without guidance.

Likewise, there are day-to-day variations in network supply conditions which assume great importance in this context, caused perhaps by the weather, lighting conditions or the use of different signal timing plans.

It should be stressed at this stage that day-to-day variability is unlikely to be a negligible effect; indeed, in a recent study (May, 1991) of the travel times of pairs of drivers in Berlin 'simultaneously' making the same origin-destination movement, one equipped with a LISB (Von Tomkewitsch, 1987) route guidance device and one without, it was found that when pooling the data for pairs travelling on different days, the variability between travel times between different days was so great that it was impossible to detect a statistically significant difference in the guided and unguided mean travel times.

Secondly, on the issue of incident induced congestion, much of the advantage of a *dynamic* system must be its ability to detect and react to unexpected conditions - such as those caused by a temporarily illegally parked vehicle, road maintenance, a breakdown or an accident, which all reduce the capacity or speed of a road. The modelling of the occurrence of such incidents, and the way in which the effects are propagated through the network is a major task; it is, however, an extremely important area to consider, since the full benefit of a DRG system may only be realised in such situations. We note that incident modelling has already received some attention in the context of route guidance systems (Al-Deek et al., 1989; Breheret et al., 1990; Mauro, 1991).

3.3 Network supply model

The issues discussed in 3.1 and 3.2 relate mostly to the way in which origin-destination demand is represented. The network supply model, on the other hand, is of at least equal importance, since without an adequate representation of such aspects we cannot hope to study many of the important potential effects of DRG.

Considering the aims of introducing a DRG system and the basis upon which it is likely to be evaluated, the supply model must be able to simulate congested conditions, and in particular the relationship between the volume of traffic using a link/turn and the time taken to traverse the link / make the turning movement. This is important because, for example, the net change in total travel time in the network, caused by influencing traffic to move from using one set of links to another, will be of primary interest to the traffic authorities, whatever guidance objective is used (2.5). Furthermore, from an individual user's point of view, the evaluation should take account of the fact that there is no guarantee that a route which was deemed to be the most efficient when the control system provided the recommendations will still be the best when the driver actually uses it, due to the effect of re-routed traffic on travel times (2.6).

The supply model should also be able to simulate the relationship between turning delay and the volume of *opposing* traffic. Whilst this is important to the representation of urban networks even without route guidance, it provides the opportunity to assess the extent to which the control system is able to route traffic so as to avoid delays from conflicting movements.

As discussed in sections 3.1 and 3.2, supply conditions (such as the capacity or free flow speed of a link) may vary for a number of reasons. This may occur, for example, because of an incident or because of 'normal' daily variations (eg weather); in the case of an incident which partially blocks a road, it may be that a proper representation of the effects can only be gained if the supply model recognises lanes and lane-changing laws. These variations are the sort of occurrences which a DRG system should be able to detect and respond to. For similar reasons, the representation of the varying effect on capacities of traffic signal settings is of great importance, particularly when these are set according to a traffic responsive scheme. Indeed, in view of the fact that it is very likely that any DRG system implemented will at some stage be integrated (and jointly optimized) with dynamic traffic signal control, it could be argued that an accurate model of signals may be of equal importance to obtaining a sound model of DRG.

Finally, when introducing dynamic models of departure time (see 3.1), a number of issues arise as to how streams of traffic, starting their journey at different times and/or from different origins, will interact downstream in the network. For example, the modelling of first-in-first-out queuing discipline may assume great importance in such a context (Smith & Ghali, 1990).

3.4 Network definition

Thus far, in discussing the supply model, we have referred to 'the network' as used by drivers. The guidance control system, on the other hand, is likely to have a quite different network within which to provide recommendations.

The problem of which roads to include in the 'guidance network' (that is, the subset of routes in the whole network from which the control system may choose the recommended ones) is a controversial one, with a potential conflict between the three most oft-quoted aims of route guidance - of improving congestion, safety and environmental conditions. On the one hand, as Brett and Estlea (1989) mention, it has been argued that a system which claims to recommend optimal routes should be able to consider all possibilities, and not just (say) the major road network. Indeed, in highly congested cities, where all the major routes are already close to capacity, the system may be efficient only if all possible routes are considered. (This may have been the reason why local authorities in London were apparently not consulted over the definition of the guidance network for the forthcoming Autoguide experiments). On the other hand, local authorities are unlikely to want 'rat runs' included in the network - for obvious safety reasons - and may wish to exclude other roads on environmental grounds. Indeed, they may even consider that congested major roads are a reasonable price to pay for deterring traffic from using residential areas, particularly when most traffic is long-distance.

What implications does this have for modelling? Firstly, a route guidance model should be flexible in terms of the network considered by the control system; it is likely that this will need to differ from the network assumed to be available to the drivers, with some roads excluded or at least penalised. Secondly, with the definition of the network being such a sensitive but crucial aspect, it would be highly desirable for the model to be able to feed into an environmental prediction (see Ayland et al., 1991, for example) or safety prediction model (TRRL, 1991). Finally, it has to be recognised that - whatever the guidance network - drivers may still choose to use routes which are undesirable to the local authorities. It could be argued that *restricting* choice is not within the rôle of route guidance; it has been suggested that this should be the responsibility of traditional traffic management measures or even a road pricing scheme (Brett & Estlea, 1989).

3.5 Longer term effects

Throughout this paper, we ignore the possibility of a feedback from the introduction (and growth in popularity) of a guidance/information system, to influence longer term aspects such as the extent and location of travel demand (that is, aside from any underlying changes which are independent of such systems).

From day to day equipped drivers are likely to adjust their departure time in the light of information given about prevailing traffic conditions; over a longer period of time, the user will become more informed about the typical temporal variation in traffic conditions (Mahmassani & Chen, 1991). With such information, the user is likely to approach the choice of an 'optimal' timing of his trip. A short-term effect of guidance/information may then be a general change in departure time for equipped drivers.

A second possible (short term) change is an increased use of public transport; Boyce (1988) suggested that this would be as a result of improved information about public and private systems, since (without information) travel times by public transport tend to be overestimated and those by private car are likely to be underestimated. Whilst one would expect the provision of route guidance information to reduce the actual travel time by private car, one may also expect public transport systems to operate with improved efficiency.

Over the medium term, route guidance systems are likely to result in an increased demand for travel (Stergiou & Stathopoulos, 1989). This will firstly be due to equipped drivers, who will travel more frequently, because their trips are more efficient. Secondly, suppressed demand is likely to emerge - that is, in general, people deterred from travelling at the moment by congestion will find travel more appealing when the network as a whole operates more efficiently.

Finally, there are likely to be long term effects such as changes in residential/job location, household activity patterns and car ownership (Boyce, 1988; Stergiou & Stathopoulos, 1989; Pickup & Polak, 1989). For example, commuting time is believed to be an important factor in the choice of housing or employment location; again based on the premise that travel times by private car tend to be underestimated, it has been suggested that an information system may supply the possibility for households to choose locations with lower commuting times (Boyce, 1988).

A final, long-term relationship which may be considered is the effect on market penetration of the guidance system. For example, the (perceived) performance of the system by users will influence the opinions of potential future users. The decision as to whether to acquire the equipment will be based on the consideration of monetary costs and perceived benefits of the system (Mahmassani & Chen, 1991).

4. DRIVER BEHAVIOUR

In this section we shall discuss issues relating to driver behaviour (whether or not they have access to DRG), within the framework of the model of supply and origin-destination demand suggested by section 3, and given the modelling requirements of the DRG control system outlined in section 2. Since the behavioural feature of most interest in the simulation of DRG is route choice, we shall concentrate almost entirely on this aspect. Secondary features - such as departure time choice - have been dealt with elsewhere in this paper (eg see 3.5).

4.1 Initial conditions

At this stage it seems appropriate to mention the importance of the behavioural rules which determine route choice *before* the DRG system is introduced.

A number of researchers (Koutsopoulos & Lotan, 1989; Breheret et al., 1990; Van Vuren & Watling, 1991) have found that the assumptions about the state of the network before guidance is in operation greatly influence the conclusions drawn about the performance of the control system. Calibration of the model is, as always, an important issue, but it has some interesting implications in the context of route guidance modelling. Specifically, it is difficult to imagine a route choice model without some form of route cost minimising (utility maximising) rule underlying it - whatever decision framework this is carried out within (eg decisions under uncertainty, as in conventional stochastic equilibrium models; see also 4.4). Travel time is likely to be an important factor in the definition of travel cost. The control system too - when providing guidance to aid the individual user - is likely to be based on route cost/time minimising principles. The calibration exercise, then, will strongly affect the extent to which a driver without guidance is deemed to fail in reaching the goal of the control system, and thereby will virtually set the maximum possible benefit of route guidance.

Furthermore, the initial conditions of the network assume great importance when we allow for the fact that when receiving guidance information, drivers will still have some loyalty to the routes they used before guidance was in operation (a reasonable assumption, borne out, for example, by the experiments of Khattak et al., 1991). Thus in a situation, say, where route guidance suggested that the driver follow an unfamiliar route which was expected to be quicker, he may choose to ignore the advice because it is easier and less stressful to remain on the route he uses regularly. For example, the concept of a Boundedly Rational User Equilibrium (Mahmassani & Chang, 1987) has proved to be useful in modelling such behaviour in a dynamic information context (Mahmassani & Jayakrishnan, 1990). Such an equilibrium is attained when no user is dissatisfied with their choice of route; the behaviourial rule is that a user will switch from their current path to an alternative only if the (relative) saving in journey time is perceived to exceed some threshold value (the switching thresholds potentially varying with time, location in the network and the characteristics of the user). It has been shown (Mahmassani & Chen, 1991) that in such a situation, initial conditions significantly affect the conclusions drawn about the performance of dynamic information and guidance strategies.

4.2 Heterogeneous driver population

In section 3, we questioned the application of the user equilibrium model to the simulation of DRG systems on the basis of the static supply/demand and equilibrium principles. We shall now examine the assumption of a homogeneous population of drivers, all assumed to have the same route choice criterion, the same definition of 'cost' and the same knowledge of the network.

For one clear reason this assumption is inadequate in a route guidance context, because some vehicles will be equipped with a guidance device and others not (assuming the installation of such equipment to be a voluntary, rather than compulsory, act). We therefore have at least two groups of driver, with different levels of knowledge of network conditions. The guided drivers could be further subdivided according to the criteria used to compute their recommended routes - for example, depending on whether the controller provides routes which benefit the individual or the system as a whole (see 2.5). Indeed, one could envisage a system being available in which the driver could request the measure to be used in computing his recommended route. Even if the route recommendations do not differ in this way, there will still be a diversity of route choice criteria in the driver population (for example minimisation of time, distance, number of stops, number of opposed turning movements or use of minor roads - see, for example, Taglicozzo & Pirzio, 1973; Wootton et al., 1981; Jeffery, 1987; Dufell & Kalombaris, 1988; Kitamura & Jovanis, 1991), which may conflict with the measures used by the control system. Such a situation may even warrant the use of a microscopic model, in which the objectives of each individual driver is taken into account. At the other extreme, we note that conventional assignment models are also open to generalisations in which the driver population is divided into different 'classes' (Daganzo, 1983; Van Vliet et al., 1986); such an approach may also allow progress with future dynamic, yet still macroscopic, models.

The final reason for requiring that the model is able to represent a diversity of behaviour across the population is in order to take account of the dependence of the reaction to the information provided on the characteristics of the trip/vehicle/driver. For example, a variation in response according to trip purpose is likely to occur; at two extremes, we could imagine the driver population being divided into a group of regular commuters and a group of tourists - studies have suggested that compliance with the guidance given is dependent upon the familiarity with the network (Bonsall et al., 1991). On the other hand, we should point out that it has been argued (Kitamura & Jovanis, 1991) that tourists could be neglected since they are more interested in navigation than dynamic information - that is, they would use in-vehicle equipment more for certainty of locating their destination, than for finding an efficient route - and in any case would in many situations represent only a very small proportion of those equipped.

Other authors have suggested socio-demographic attributes may affect the likelihood of responding to the information (Kitamura & Jovanis, 1991; Mahmassani & Chen, 1991); for example, studies have indicated age (Haselkorn et al., 1989; Bonsall et al., 1991), sex (Khattak et al., 1991), income and stress threshold (Haselkorn et al., 1989) of the driver as significant factors in his/her reaction to dynamic guidance/information (although we do not seek to suggest that there is a consensus of opinion on the significance of such factors - many of the findings are indeed contradictory). The question of modelling driver response to information is considered further in section 4.4.

4.3 Response of unequipped drivers

It appears that the great majority of route guidance simulation studies performed to date have assumed that unequipped drivers will use the same routes they followed before guidance was in operation, independent of the behaviour of equipped drivers. An alternative (and, to some extent, at the other extreme) is to assume that they are able to (or at least seek to) find new routes consistent with the same behaviourial rules they used to find their route before guidance was in operation, but now based on the new route choice of the equipped drivers. These two extremes of behaviour have been investigated to some extent, with widely differing conclusions. Breheret et al. (1990) found - when investigating a strategy which recommended a single route per movement for the whole peak period - that very different conclusions could be drawn in the two cases, warning that such 'a conceptually poor guidance strategy ... can be apparently successful ... because of the flexible response of unguided drivers to the worsening conditions on the guided routes'. Watling (1990) on the other hand, investigated a static multiple route (per movement) guidance strategy, in which the recommended routes were chosen so as to achieve a combined equilibrium between the success of the unequipped drivers in satisfying their route choice objectives (based on imperfect knowledge of network conditions) and the equipped drivers who have perfect (or at least better) information. Under the assumption that the control system is able correctly to predict the response (ie whether 'full' or 'none') of unequipped drivers, it was found that their assumed response had virtually no influence on the network or user benefits of user optimal guidance.

In reality, the response is unlikely to be at either of these two extremes; there are a number of schools of thought on this matter. On the one hand, it has been suggested that the day-to-day changing in trip behaviour of equipped drivers will mean that unequipped drivers will be faced with conditions which are more difficult to predict than they were before guidance was in operation (Bonsall & Parry, 1990). Even though they may rightly believe that more efficient routes exist, they may stay loyal to the one(s) they used before DRG was introduced - either because they are averse to experimenting with new routes in such unpredictable conditions, or because their knowledge of network conditions does not allow them to find a better route. Alternatively, it could be argued that if only a small percentage of drivers receive guidance, then unequipped drivers are unlikely to perceive any significant change in conditions; it would then seem reasonable to assume that unequipped drivers behave no differently to the case when guidance was not in operation.

As a converse to the opinion that the unpredictability of traffic conditions may be increased, the effect of DRG may be to make conditions more stable (CAR-GOES, 1990; Mauro, 1991). By informing equipped drivers of incidents, and influencing them to re-route, there is the opportunity to reduce variability in network conditions. Furthermore, in cases of recurrent congestion, there is likely to be a repeated, historical trend in the recommendations provided (see 2.2) and the resulting response of equipped drivers. These two conjectured effects suggest that whilst network conditions may change significantly due to the introduction of DRG, they are likely to settle down to a less variable state. Thus unequipped drivers will have an incentive to change from their choice of route before guidance was in operation, and with less variability may find it easier to determine an efficient route.

Until the introduction of full-scale field trials with a significant number of drivers equipped, we are unlikely to have any idea regarding the response of unequipped drivers; this is due to the fact that this response will depend on that of equipped drivers, a sufficiently difficult problem in its own right. Before that time, any model of 'partial' response of unequipped drivers will be very difficult to calibrate; sensitivity testing is the only alternative.

4.4 Response of equipped drivers

It is appropriate that a discussion of the modelling of DRG systems concludes with the consideration of driver response to the information provided, for this has been seen to be a recurring issue throughout all aspects of the modelling task. Summarising, it is possible to identify a number of different themes which may be used to classify the various factors (with the relevant sections of the paper given in parentheses).

Firstly, there are those aspects of the model relating to the interface between the on-board equipment and the driver, such as the delay between receiving guidance/information and actually responding to it (2.3), and such as the frequency at which the equipment is consulted and the dependence of this frequency on the type of advice provided (2.3). Secondly, there is a diversity of response which is likely to be elicited among equipped drivers, according to the characteristics of the driver and the purpose of the trip (2.3, 2.4, 4.2). Thirdly, when studying guidance objectives which are based more on the considerations of the system as a whole rather than the individual user, there is the need to recognise the dependence of drivers' compliance with the guidance on the perceived user benefit (2.5). In such cases, it may be necessary for the model to simulate an integrated system of road pricing, to study the extent to which this would be able to enforce such route recommendations (2.7). Fourthly, a number of issues have arisen concerning the credibility of the system, related to the type and quantity of information provided (2.3), the consistency of information over different days (2.5) and the stability of the route recommendations for higher levels of market penetration (2.6). Credibility is related to a driver's confidence in the guidance system and will affect his response in the longer term; it is likely to be a rather difficult factor to model, but at least account should be made of it when interpreting simulation results. Finally, there is a need to model the dynamics of the decision-making process of drivers receiving information/guidance during their trip (3.1), with choices made on a junction-by-junction basis (2.4). This is likely to be particularly important when simulating the occurrence of incidents (3.2), although the behavioural law in such cases may be different to that under non incident conditions.

Many of the features described above could not be accommodated in established models of route choice; indeed, it is apparent that little effort has been expended in the past on trying to understand the behavioural processes which form the basis for route choice, even without DRG. This has come to light since it is now clear that in order to evaluate the benefits of DRG, it is unsatisfactory to assume that every individual driver possesses the same mental processing capabilities as we would expect of the control system - able (and willing) to handle large amounts of data, to account for temporal and spatial variations as well as normal day-to-day variaibility, and to compute from this information his best choice of route. In the second part of this section, then, we shall discuss some possible bases from which a new framework for driver response could be developed.

The extent of a driver's knowledge of the network in which he is driving (or, put in its crudest terms, whether a driver is 'familiar' or 'unfamiliar' with the network) arises a number of times within this paper as an important explanatory factor in driver response. Gould (1989) discussed (increasing) levels of spatial knowledge: 'landmark' (in which the spatial relationships between known sites is incomplete), 'route' (in which there is some sequence to the landmarks) and 'survey' or 'map' knowledge (in which topology, distances and angles are included within a person's mental map). Spatial knowledge is always incomplete, will never fall precisely into one of the three categories above, and varies between individuals. Thus, it is conjectured, different drivers will receive different benefits from an information/guidance system. It is interesting to note that - with relevance to the 'map' category above - in an attitudinal survey (Khattak et al., 1991) in which the number of alternative routes known to a driver was taken as a proxy for his 'cognitive map' (the long-term, stored map information - see Freundschuh, 1989), it was indeed found that a driver's diversion response to delay was influenced by such spatial knowledge.

The importance of the learning process has been recognised by a number of authors (Joint, 1990; Van Berkum & Van Der Mede, 1990; Kitamura & Jovanis, 1991). This comprises both learning how to use the information/guidance system as well as learning about traffic conditions. This takes place in an individual's repeated use of the network, and will affect his knowledge of alternative routes, his knowledge of typical network conditions, his confidence in the information system and his development of decision rules to utilise such information.

The decision rule a driver uses as to which route to use is one made under uncertainty; the driver does not have perfect knowledge of the network, and in any case conditions vary from day to day. This decision rule may take many forms, of course. For example, there is the conventional stochastic user equilibrium model (Daganzo & Sheffi, 1977), which aims to model differences in perceptions due to such uncertainty. Others have suggested that decisions are based on heuristics and may even be irrational (Joint, 1990). The concept of a 'threshold' adds a still further option (Mahmassani & Jayakrishnan, 1990); this arises from evidence that drivers base their decisions on minimum perceived travel time differences (thresholds). In a route guidance context, a driver's threshold value will be a function of his own characteristics (such as his willingness to take risks or loyalty to his usual or known routes) and a product of his learning processes regarding the performance of the control system and experience in the network. A possible rule is then that a driver will change from his regular route if an alternative (or advised) route is perceived to be a certain percentage quicker.

We have described above just a small number of possible ways in which driver response may be handled; in developing a suitable model, it may be necessary to combine a number of approaches. The improved behavioural understanding which should then arise will not only enable a proper evaluation of DRG to be carried out, but will also provide feedback to suggest new, more effective guidance strategies, tailored to driver requirements.

5. SUMMARY

In this paper we have discussed the modelling of a control system for dynamic route guidance, as well as the implications this has for the representation of the network supply and demand conditions and of driver behaviour. In particular, we have identified areas in which established modelling practice is unable to address the necessary simulation tasks and have suggested some of the key factors to consider in developing any new model.

We hope that this paper will prompt even further exchange of ideas between those involved in modelling such systems, as well as providing a framework for those wishing to assess the many simulation results currently appearing. As this paper has indicated, there are still a great many researchable topics in both of these areas.

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