New Dynamic Model to Evaluate the Performance of Urban Traffic Control Systems and Route Guidance Strategies

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A dynamic assignment/control model for evaluating urban traffic control schemes and route guidance strategies is described in this paper. The model, which has been developed recently at the University of York, United Kingdom, uses the dynamic assignment program CONTRAM. For each fixed road network, subject to a given overall pattern of dynamic demand, the model currently evaluates all eight possible combinations of (*a*) four responsive traffic control policies, and (*b*) two route-guidance strategies. The model assumes that the route-guidance is accurately obeyed. The model gives results for all required demand levels. Preliminary results of applying the model to one artificial network and one realistic network are also presented. Further extensions are in hand to take some account of (*a*) drivers' variable compliance with guidance, (*b*) the effects of different traffic signals following different control policies, and (*c*) drivers' ability to select their own departure time. At the moment, the model requires that the road network is fixed, and does not seek to mimic the dynamics associated with the beginning and end of an incident. Good communications with drivers will help to ensure that the guidance advice is obeyed; but for system-optimal-like guidance strategies a supportive, well-communicated, road pricing system may also be necessary to obtain such obedience. The model described here will clearly be useful for assessing the consequences of different road pricing strategies in a dynamic setting.

A dynamic assignment model to evaluate traffic control systems and route guidance strategies is needed. The performance of urban road traffic networks is of major importance for travelers, nontravelers, transportation engineers, and town planners. Yet there is currently no computer model which is trusted to provide realistic estimates of traffic network performance.

Current simulation programs (such as NETSIM) accurately represent small-scale interactions but do not model route-choice decisions and, on the other hand, most current assignment programs do not have accurate, dynamic, simulations of the detailed interactions between traffic flows and signal controls at junctions; nor do they allow a range of control systems.

It is clear that, in reality, network performance depends on both network-wide properties and on the intimate detail of particular junctions including the effects of traffic control, at least in part because both affect the routing decisions of drivers. So there is no escape from the need to somehow estimate the networkwide effect of local interactions (including responsive control and drivers' route choices) if network performance is to be accurately estimated.

Recent attempts to study the benefits of route guidance have made this need more clear and more urgent; the European DRIVE project is now sharply feeling the lack of a reliable, reasonably fast, network model which can test various control and routing strategies in a realistic, dynamic, setting.

While the need for a good dynamic assignment model has been highlighted by the particular current wish to evaluate dynamic route guidance strategies, such a model is also essential if we are to evaluate responsive traffic control systems even if route guidance is not involved. Responsive control systems, without route guidance, are becoming increasingly sophisticated and increasingly used; a thorough scientific evaluation of these systems is very long overdue. The only way to perform such an evaluation is by using a good, flexible, dynamic, control/assignment program.

Mahmassani et al. (*1*) acknowledge the difficulty of assessing the likely performance of a real urban traffic network; they suggest that "the complex interactions in a traffic network effectively preclude the analytic derivation of macroscopic network-level relationships from the basic principles governing microscopic traffic behaviour . . . ." Mahmassani et al. proceed to outline an approach to network modeling using Herman and Prigogine's (*2*) two-fluid theory of town traffic, and give some results of simulation experiments. These authors acknowledge the limited nature of their experiments, which do not allow for either drivers' route choices or the detailed influences possible with modern responsive control systems.

A new dynamic model for assessing traffic control system and route guidance strategies is described in this paper. This model has been obtained by extending the dynamic assignment program CONTRAM (*3–5*), developed in 1978 by the Transport and Road Research Laboratory in the United Kingdom.

THEORETICAL BACKDROP

The need to take account of the effect of control on assignment was pointed out by Allsop (*6*). Smith (*7–10*), Smith et al. (*11*) and Smith and Ghali (*12*) have studied the theory involved when control and assignment are combined, and Heydecker (*13*) has pointed to some difficulties which arise when detailed models of junctions are incorporated into an assignment model. Throughout this theory demand is supposed to be steady as time varies.

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Smith and Ghali (*14*) present some control/assignment results for a gently rising rush hour and a new theoretical approach to dynamic assignment with fixed signals. The dynamic assignment theory is severely limited by the assumptions needed; nonetheless the authors are not as pessimistic as Mahmassani et al.

RECENT TECHNOLOGICAL ADVANCES AND THEIR IMPLICATIONS FOR NETWORK MODELS

Traffic control systems that respond cleverly and rapidly to existing traffic flows and queues are now capable of being provided. Using new communication methods, it is hoped that the ability to respond to the needs of individual travelers will come soon; by giving route guidance, or by choosing signal-settings which are appropriate for certain routes, for example. And the practicality of road pricing has increased dramatically as a consequence of "smart cards."

But these technological opportunities have not been matched either by a corresponding improvement in our understanding of road traffic networks or by corresponding developments in the computer modeling of traffic networks; 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 without proper evaluation. Indeed it is likely that some technologically sophisticated traffic control schemes are now aggravating the congestion which they were designed to reduce! It would surely be best to reduce—or even eliminate—the possibility of this happening with route-guidance; by immediately (*a*) ensuring the development of a sound theory, and (*b*) developing a good dynamic traffic assignment program.

DESIGNING AND TESTING A TRAFFIC CONTROL SYSTEM

The obvious way to test the networkwide effect of an urban traffic control scheme is by using computer programs. The lack of an appropriate network model means that such tests are currently impossible; and so control systems are often first tested on the real-life road networks themselves. [See Holroyd, et al. (*15*), Holroyd and Robertson (*16*), Tarnoff (*17*), and Henry et al. (*18*), for example.] Such tests are expensive, and (at least when the network is congested) are difficult to interpret because of demand and other changes which, in real life, cannot be controlled, and have major effects. Moreover the results of these tests have often been negative, and sometimes *very* negative, at least when congestion is severe.

The need to control certain aspects of the problem even during computer tests has recently led to the creation of an option which fixes certain demand and routing aspects of NETSIM; without such options meaningful control experiments become difficult and essentially unrepeatable. Such options, fixing certain aspects of the problem while the effect of varying others is studied, cannot exist in real life!

Assuming that we wish to create a computer program which models a particular road traffic network with particular traffic signals and a specified dynamic demand; the central questions we seek to answer are:

1. For a given control response, what dynamic traffic flows will occur?
2. How should traffic signals respond to changing traffic?

Question 1 is a problem of prediction, given a specified control system operating in a specified way. Question 2 will also apply to a particular network equipped with particular control facilities; but this question is far more open-ended than Question 1; designing a good control response is far harder than predicting the outcome of a specified response. It is essential that Question 2 is answered if good control systems are to be designed.

DESIGNING AND TESTING A TRAFFIC CONTROL/ROUTE GUIDANCE SYSTEM

If dynamic route guidance is considered as a possibility for influencing road traffic, Questions 1 and 2 become

1′. For a given control response, and a given route-guidance strategy, what dynamic traffic flows will occur?

2′. How should traffic signals and routing advice respond to changing traffic?

If the signals and the route guidance are intended to react quickly to current traffic conditions, then Question 2′ requires a rapid response. This will be the case, in particular, if response to an incident is to be provided. None of these questions can be answered convincingly now because (*a*) the required theory is insufficiently developed, and (*b*) the tools necessary to study congested network performance, by using simulation on computers, do not exist.

The Sharp Questions

While the main function of Science is to explain and predict, an important function of mathematical models is to pose "sharp questions." Answers to Questions 1 and 1′ will clearly be fulfilling the main function to some degree—but Questions 2 and 2′ are sharp questions that require the careful development of a theory as well as the careful development of a rigorous dynamic model to test the theory. Sharp questions are important because they force one to try to get to the heart of the matter. The theory of traffic control and route choice in a dynamic setting is currently in a very underdeveloped state, and an appropriate dynamic network model involving both route-choice and traffic control does not exist.

Requirements of a Traffic Control/Route Guidance Network Model

For any specified network it would be sensible to use the network model so as to determine (traffic control policy, route-guidance strategy) pairs which produce good results, on the particular network, when taken together. [The new modification of the CONTRAM program allows this to some degree. As currently formulated, the program shows the consequences of a (control policy, route guidance) pair on the assumption, at the moment, that the route guidance is obeyed.]

If the model is really very fast, and includes a reasonable estimate of drivers' reaction to guidance, then the model could be used for on-line control and guidance; otherwise (and this is certainly the only hope at the moment) the model should be utilized off-line to generate a library of (traffic control policy, route guidance strategy) pairs and hence a library of (control, guidance) plans which are selected on-line in the light of current traffic conditions.

TWO EXISTING MODELS

There are two network models which have been used for assessing traffic management schemes in the United Kingdom. Both attempt to embrace both local detail and the networkwide assignment of traffic to routes according to reasonable route-choice principles; they are called CONTRAM and SATURN (*19*). Broadly speaking, SATURN captures the variety of local junction interactions better than CONTRAM, while CONTRAM has a more accurate representation of drivers' route-choice decisions in a dynamic, rush-hour, context. Of course, it is plain that in designing an assignment model which represents both junction detail and the dynamics of route-choice, some compromises have to be made. An extremely detailed dynamic assignment model with extremely precise local detail would, in the current state of the traffic modeling art, have an impossibly long running time on large realistic networks. In trying to improve upon current models it must be borne in mind that there are some theoretical problems which arise when accurate junction detail is included in a traffic assignment model: with certain junction delays assignment algorithms may not converge, and may also converge to different answers if the process is begun at different starting points; see Heydecker (*13*).

Neither CONTRAM nor SATURN, as they stand, is able to answer Question 2′ very well because both lack the flexibility to represent various control options conveniently and both have only one routing principle. Nonetheless both CONTRAM and SATURN have been used to test various route guidance scenarios; Breheret et al. (*20*) and Smith and Russam (*21*) used CONTRAM to assess, respectively, the likely benefit of (*a*) guiding drivers along their best routes accurately, and (*b*) using AUTOGUIDE in London. Van Vuren and D. Watling, in a paper in this Record, have used SATURN model to estimate the likely benefits of route guidance under a variety of circumstances. These studies both required detailed changes to the standard program.

In the work at the University of York CONTRAM was modified so that is can deal with a variety of control policies and a variety of route-guidance possibilities. It is hoped that the extended model will be used to test a whole spectrum of (traffic control policy, route guidance strategy) combinations. In this paper first results are given; the methods are more or less readily applicable to most real-life networks, although at this stage the model assumes that route guidance is obeyed.

Charlesworth (*22*) obtained similar control results in 1977 by linking a well-known steady-state assignment program to the TRANSYT signal optimization procedure. Although the dynamic assignment program CONTRAM and different signal optimization procedures are used in the present research, the basic idea is similar to that suggested by Allsop and employed in Charlesworth's paper.

CONTRAM

CONTRAM is a dynamic assignment model which represents, in a realistic manner, queueing delays as they vary in time and the routing changes which these time-varying delays are likely to cause. CONTRAM contains an option for setting the traffic signals according to a natural equisaturation policy, as well as a fixed-time option in which program users specify fixed signal settings. The program finds the dynamic flow pattern in which all drivers are using their least-time routes. This flow pattern will be called a user-equilibrium. Thus for any fixed signal-settings CONTRAM finds the user equilibrium consistent with these fixed settings; or alternatively CONTRAM finds the user-equilibrium consistent with a natural equisaturation policy. Having found the user equilibrium, CONTRAM prints out many figures which indicate the performance of the network. Much information about CONTRAM is contained in three reports, by Leonard et al. (*3*), Leonard and Gower (*4*), and Taylor (*5*) published by the Transport and Road Research Laboratory (in the United Kingdom).

New CONTRAM Extensions

In this paper we outline some extremely recent modifications and extensions of CONTRAM carried out at the University of York, United Kingdom. These allow the user to estimate the performance of traffic networks under a somewhat wider variety of (traffic control policy, route guidance strategy) combinations. We shall also give some results of applying our new version of CONTRAM to one artificial and one realistic network.

We have modified CONTRAM to accommodate

- A second route-choice strategy, and
- two further control policies.

The route-choice principle is that, perhaps because they are guided, drivers choose to travel along routes whose links have, in total, the least local marginal cost. Here the local marginal cost of traversing link i, beginning at some time t, is the additional cost caused to all users of this particular link by one additional vehicle entering this link, at this time; assuming that the signal-settings (and other drivers' route-choices) remain fixed. These routes do not cause least increase in the total travel time spent on the network; they are not routes of minimum marginal cost—they are routes of minimum local marginal cost. If the signal settings are fixed, the flow pattern which CONTRAM then calculates will be called a local system-optimal flow pattern for those fixed signal-settings.

The two further control policies are P_0 and local delay-minimization. The policy P_0 is introduced and discussed further in Smith (*7–10*). Operating in a steady-state context, the policy P_0 maximizes the capacity of a network (provided certain natural conditions are met).

The local delay-minimization policy minimizes delay at each junction for the dynamic flows which currently impinge on that junction. (The policy does not minimize delay for the network because it ignores two effects of a control change at the "current" junction. First, it ignores changes in the flows impinging on downstream junctions arising from changes in the throughput at the current junction. Second, it ignores routing changes as drivers react to changed travel times.) Our local delay-minimization policy chooses green-times which maximize throughput at each junction on the assumption that the junction is isolated.

Table 1 summarizes the (traffic control policy, route guidance strategy) combinations that can be studied with the program. Of these eight combinations only two come with the original CONTRAM. On the other hand, some of these combinations are unnatural and so would not be of much interest. We can also model mixtures in which some vehicles follow the user-equilibrium strategy and some follow the local system optimal strategy, and in which some junctions are controlled according to one control policy and some are controlled according to another. Furthermore, a spectrum of routing strategies between local system optimal routing and user equilibrium routing and a similar spectrum of control policies can be modeled. These possibilities allow the estimation of the likely consequences of only partial driver and signal compliance with the guidance strategy and the control policy respectively. Plainly, a truly vast spectrum of control/routing possibility is opened up, although not all combinations are of interest.

Modeling Assumptions and Their Relevance

As far as current results are concerned, the road network, including such items as the lane markings and saturation flows, is regarded as fixed; so incidents are not being modeled directly at the moment. All the results here are concerned solely with the minute-to-minute and day-to-day interaction between the control system and the routing strategy, assuming that network characteristics stay the same and any guidance is accurately obeyed. We shall primarily be concerned with this interaction when there is significant or severe recurrent congestion on at least part of the network.

The results involving local system optimal routing will be most relevant if a supportive road pricing system is either in force or being contemplated. But these results are also relevant if guidance is related to an incident or special event on the network which (*a*) renders drivers' knowledge of the network ineffective, and (*b*) creates a more urgent need to maximize effectiveness. Nonetheless in this paper no incident related results are presented, and the road pricing issue is not commented upon. The model would perhaps be useful if the network is changed for a significant period of time by an incident; as it could be applied to this altered network. But at the moment the model does not apply to the transient dynamics which immediately follow the beginning and the end of an incident.

Here the departure times of vehicles are supposed given. The program was extended further to allow for the ability of drivers to choose their departure time in the light of anticipated congestion and their desired time of arrival.

RESULTS

In presenting the results we have chosen to imitate the graphical form of the ordinary single link cost flow function; but here we draw a graph of total travel cost (or time) as the demand level increases. To obtain the graphical results, first a network, a control policy, a dynamic demand, and a (control, routing) pair are chosen. Then, for a proportion p of the fixed demand, the modified CONTRAM model is used to determine the dynamic (traffic control policy, route guidance strategy) pair which satisfies both the route-choice strategy (user equilibrium or local system optimal) and the control policy (fixed-time, equisaturation, P_0, or local delay-minimization at the moment). Then the total travel cost (or time) incurred is calculated for this proportion p. Finally we have increased the demand level p from 0 to 1, in steps of 0.1, and plotted the total cost as a function of p, joining the ten data points by a smooth curve.

In the results presented in the next subsection, the equisaturation policy and the local delay-minimization policy are called equisat and delmin, respectively.

First Realistic Results

These are summarized in Figures 1 and 2. For each demand level there are eight possible total costs according to the (control policy, routing strategy) combination employed. (Some combinations are of little interest.) For an increasing sequence of time-varying demands, the number of vehicle minutes spent for each control/routing combination is shown. The results suggest that on this network local system optimal route-guidance, if totally complied with, together with either of the

TABLE 1 TABLE SHOWING THE (CONTROL, GUIDANCE) PAIRS WHICH CAN BE TESTED BY (*a*) THE ORIGINAL CONTRAM PROGRAM, AND (*b*) THE NEW EXTENDED VERSION OF CONTRAM

CONTROL POLICY	GUIDANCE STRATEGY	
	User equilibrium	Local system optimum
Fixed time	CONTRAM	Extended CONTRAM
Equisaturation	Extended CONTRAM	Extended CONTRAM
Local delay minimisation	Extended CONTRAM	Extended CONTRAM
P_0	Extended CONTRAM	Extended CONTRAM

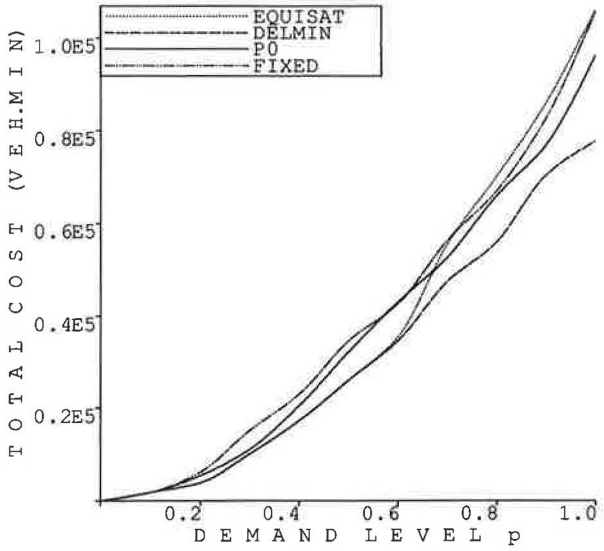

FIGURE 1 Performance with user equilibrium routing and four control policies.

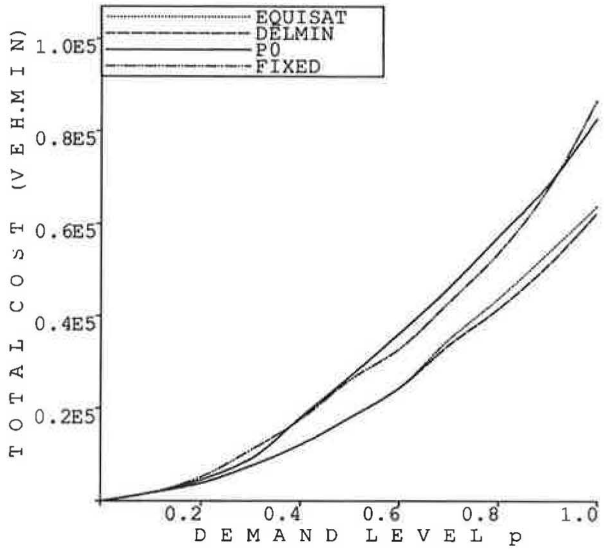

FIGURE 2 Performance with local system optimal routing and four policies.

two familiar policies, may be expected to reduce total travel times by at least 20 percent; and that the control policy (with no route guidance) may be expected to cause the total travel time to vary by about 10 percent. The equisaturation policy is a natural extension of the well-known Webster's method to our current case in which there are queues. It is the existence of these results which holds promise for the future; the actual results presented here are relatively unimportant—they derive from one undoubtedly unrepresentative network. Here only these further observations on this example are made:

1. The performance of the equisaturation policy improves dramatically under local system optimal routing.

2. Local delay minimization is the best control policy with both routing assumptions.

The most important feature of these results is their existence; bearing in mind that they derive from a pretty realistic dynamic model of a realistic congested road network. The network is shown in Figure 3; a much altered part of a town in England; and the stage structure of some junctions is shown in Figure 4.

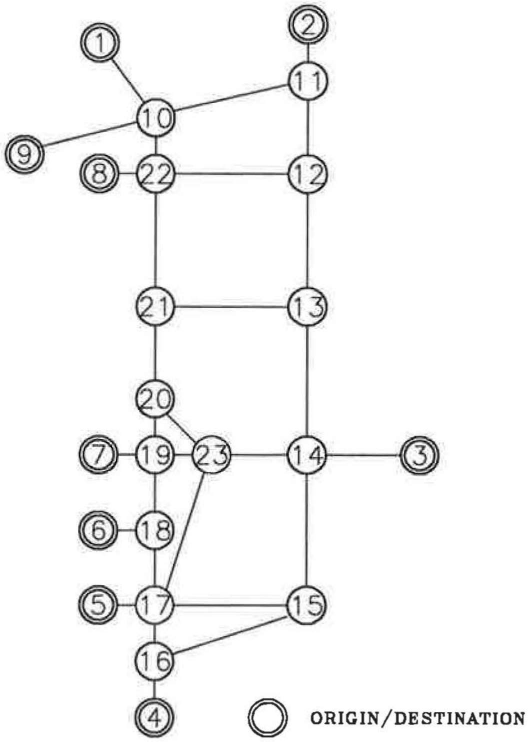

FIGURE 3 Network geometry.

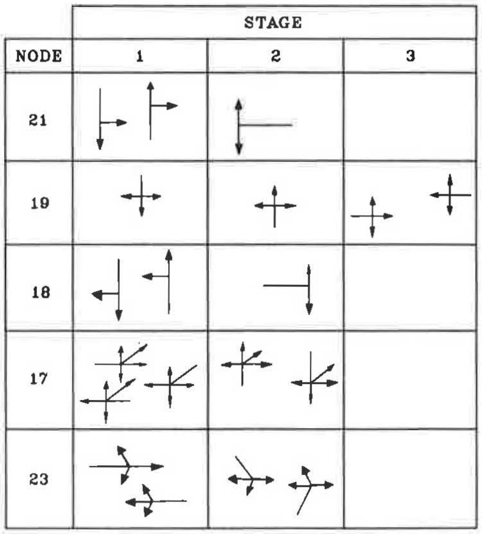

FIGURE 4 A selection of signal stages.

Results Obtained Using an Artificial Network

In these tests only user-equilibrium routing was considered. Figure 5 gives the network geometry: the unlabeled junctions are signal-controlled and those marked F are fly-overs or very large junctions offering, on average, zero or very slight hindrance to traffic flow. Two different choices for the unlabeled, controlled, junctions were considered. In the first, all eight signalized junctions are identical and symmetrical; the results are shown in Figure 6. In the second, each central route is far wider (in fact six times wider), at the signalized junctions, than the outer eight routes. The results here are given in Figure 7. With symmetrical equal junctions, P_0 and the equisaturation policy are identical and so give the same performance, and local delay-minimization is much worse; with the wide central route, P_0 and local delay minimization have similar performances and the equisaturation policy is much worse. The results shown in Figures 6 and 7 suggest that the comparative performances of different control policies are likely to be highly dependent on the detailed structure of the network being considered.

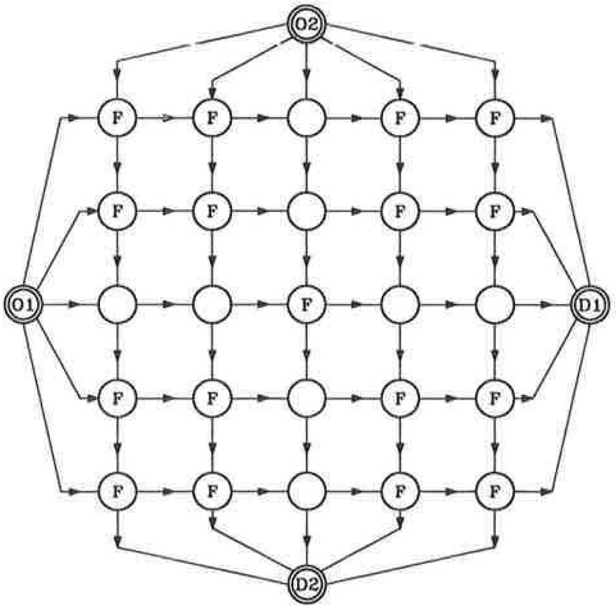

FIGURE 5 An eight signalized-junction artificial network.

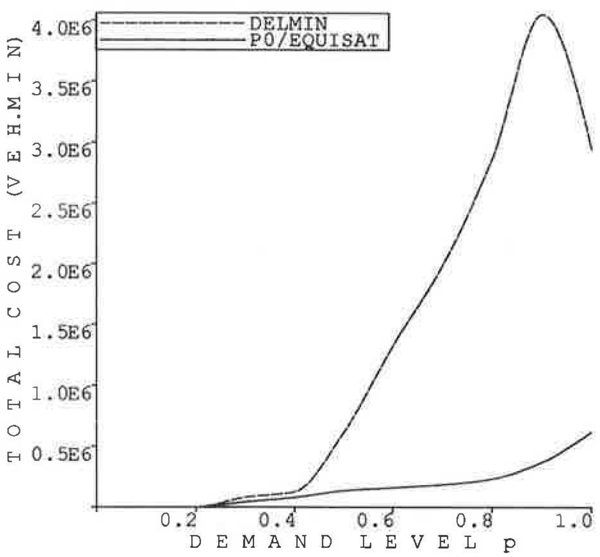

FIGURE 6 Performance of the network when the signalized junctions are symmetrical.

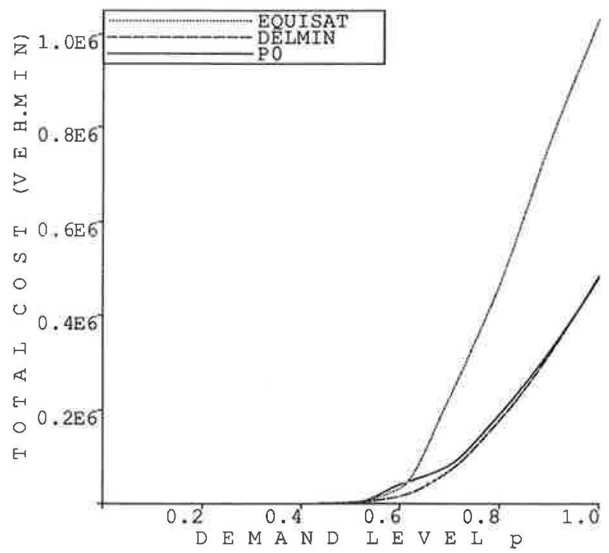

FIGURE 7 Performance of the network when the signalized junctions are unsymmetrical.

CONCLUSION

Performance estimates, summarized in Figures 1 and 2, for all eight combinations of four traffic control policies and two routing strategies (on a realistic network) using our extensions to the CONTRAM dynamic assignment program were obtained. The results suggest that, for this network and a rigid demand, performance gains due to signal control policies are likely to be of the same order of magnitude as performance gains deriving from route guidance (with road-pricing). The results for the artificial network suggest that the best signal control policy will probably depend on the network being considered: judging by these results alone, it is unlikely that a single best control policy exists. The central conclusion is that CONTRAM, together with the extensions described here, is likely to be a very useful tool for assessing the performance of signal-controlled road networks whether route guidance is involved or not. In Figures 1 and 2 each graph represents 10 data points (1 for each demand level); each data point derives from one CONTRAM assignment/control equilibration; and CONTRAM uses 13 time slices. So these eight graphs represent about the same information as that obtained in 10 × 13 × 8 = 1,040 static assignments.

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