TRAFFIC ASSIGNMENT UNDER ENVIRONMENTAL AND EQUITY OBJECTIVES

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Two recent changes in the transportation field may have a profound effect on traffic assignment techniques. The first is the increasing importance of environmental objectives, such as reducing air pollution, within the policies of traffic system authorities. The second change is the advent of the intelligent vehicle-highway system (IVHS), which, among other attributes. has the potential to be used to implement new methods of controlling vehicular emissions. The fact that historic traffic assignment techniques may. be inadequate for modeling the traffic systems that will operate under IVHS with environmental objectives--primarily when traffic follows routes that arc based on equitable rather thin . equilibrium or optimal considerations--is illustrated. Then it is shown that when IVHS policies that attempt to reduce system travel time are implemented, other objectives such as reducing environmental pollution may actually increase. A network from Ottawa, Ontario, Canada. is used as a test bed.

A number of objectives are generally associated with the proposed intelligent vehicle-highway system (IVHS). One of the most commonly cited goals is to reduce urban traffic congestion with a corresponding reduction in average trip travel time. This has been an ongoing objective of transportation authorities since the first urban traffic networks were constructed. Previously the most common method of achieving this goal was to increase capacity through building infrastructure. Another objective that is often cited is to reduce negative transportation by-products such as noise and air pollution. This has become an increasingly important goal over the last 30 years mainly because of increased public awareness of the dangers of pollution and a public willingness to reduce this pollution. Historically the primary means of reducing air pollution have been through legislated emission standards on vehicles.

This paper examines the implications on traffic networks of using the recently proposed IVHS such as the advanced traffic management system (ATMS) and the advanced traveler information system (ATIS) to achieve the goals stated above. These proposed systems may be used to achieve the objectives in either an active or a passive manner. The former would entail such things as a centralized route guidance system (RGS) in which vehicles are explicitly, given the routes that they must follow, whereas an example of the latter would be an electronic toll collection system in which drivers are free to choose their own routes bill are charged for their use of the road or the amount of pollution that then, produce. Note that in both the passive and the active systems different goals or combination of goals may be used.

The second section illustrates the need for new traffic assignment techniques that better represent the shift toward environmental objectives that has recently taken place. In the third section assignment techniques based on environmental and equitable objectives are examined on a two-node network to illustrate the concepts. This is followed by a sensitivity analysis of traffic assignment based on environmental objectives on a network from Ottawa, Ontario, Canada, to

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identify any trends on realistic networks and any potential problems in using traditional assignment procedures.

RECENT DEVELOPMENTS IN TRAFFIC ENGINEERING

Two major developments in recent years are forcing traffic engineers to reexamine the techniques and objectives of traffic assignment. The first shift is the rapid advancement in IVHS technologies, particularly in-vehicle RGSs, in which it is at least theoretically possible that drivers may be explicitly routed through the network on the basis of the routes that are calculated external to the driver or the vehicle. At a minimum IVHS technologies will influence driver route selection by providing timely information on the state of the network. For example the use of automatic toll collection on the road network or the use of changeable message signs could change the route selection process of drivers by changing the perceived attributes of competing routes.

It is often assumed that because traffic assignment is based on the concept of generalized cost the traditional assignment techniques will be applicable for analyzing IVHS. The major changes required in the traditional procedures include modeling multiple user classes (RGS and non-RGS) and modeling dynamic traffic assignment (1,2). Although very complex, these topics will not be examined here because the main purpose of this paper is to illustrate potential problems in traffic networks when different objectives are used and to illustrate the need for assignment techniques that can model equitable as opposed to equilibrium or optimal assignments. It will be assumed in all of the analyses in this paper that all drivers have the same attributes and the same access to information. Therefore user equilibrium (UE) techniques will be used for modeling IVHS in which the drivers select their routes on the basis of their own objectives, and system optimal (SO) techniques will be used for modeling IVHS in which the routes arc explicitly sent to drives and are based on system considerations.

The second change that will affect traffic assignment techniques is related to the prominent role that environmental issues have recently played in transportation project decisions, in particular the significant interest that has recently been expressed concerning the consequences of vehicular emissions. Reducing vehicular emissions has been an ongoing goal of many authorities over the past 20 years, with a number of U.S. states and Canadian provinces instituting relatively stringent pollution control programs. These programs may be defined as passive in nature, in that most regulate the emission levels from the vehicles. However the total amount of pollutant emitted by a vehicle is not regulated, and consequently there is little incentive for individual users to reduce pollution. With the advent of IVHS it is now recognized by many traffic authorities that more active measures may be used to reduce pollution. As an example it may be decided to use a centralized RGS to directly route vehicles so as to minimize air pollutant emissions during particular periods of the day or in particular locations. A more passive and realistic example would involve charging drivers on the basis of the amount of pollution that they produce (and where that pollution is produced) in the hope of reducing emissions.

Because traffic assignment techniques are based on the concept of generalized cost it may be assumed that traditional assignment techniques will also be applicable for analyzing route selection on the basis of environmental impacts. The only changes required to implement the assignments discussed above would be the development of appropriate generalized cost functions. However identification of the generalized cost function that would be used is problematic. There has been little research into which of the relevant factors (i.e., noise pollution, fuel consumption, etc.) should be included in the generalized cost function or what the relative weights for each of the relative factors should be. Regardless of which components are used in the generalized cost function it is important to note that in the context of environmental concerns the process and objectives of traffic assignment shift from factors that solely concern the individual drivers or the system operators to factors that also consider the effects on individual segments of society. That is it may not be enough to say that the individual drivers or the transportation network operators will benefit as a result of the implementation of IVHS technologies but rather that no segment of society will be unduly affected in a negative manner. For example a political decision may be made that the reduction of negative transportation by-products should be a major policy objective regardless of the impact on individual drivers. The traffic assignment techniques will have to reflect this new reality if meaningful analyses of environmental objectives and IVHS implementation are to be studied. Consequently it is not clear that the objectives of the SO or UE traffic assignment, even with an appropriate generalized cost function, will be adequate for analyzing the assignment of traffic under these new conditions.

It is useful at this point to examine (a) how the concept of equity and environmental concerns may influence the actual route selection process of the drivers and (b) how these changes may be modeled by using traffic assignment procedures.

Consider a negative product *X*, where *X* may be the noise pollution, air pollutants, and so on that are caused by vehicular traffic. It may be decided that the amount of *X* produced should be controlled through the use of an IVHS. The following is a discussion of the different objectives that may be chosen and the strategies that may be employed to meet the objective of reducing *X*. Also included are potential means of modeling these strategies in traffic assignment procedures.

It may be decided that the objective of the IVHS is to minimize the total amount of *X* produced. The objective could be achieved by giving explicit routes to the individual vehicles through a centralized RGS. The traffic assignment could be modeled by using the SO concepts discussed previously in which the generalized cost is a function only of *X* rather than of travel time.

Alternatively it may be decided that although decrease in the production of *X* is the primary objective, it would be better (i.e., politically better) to charge users on the basis of their production of *X* and let the drivers decide their own routes. In the real network an electronic toll system in which the drivers are charged on the amount of *X* that they are responsible for producing would be set up. This is directly analogous to "occasioned cost" pricing, whereby consumers (drivers) pay only for what they directly consume. This type of system could be modeled by using a standard UE traffic assignment, with *X* being the sole parameter in the generalized cost function.

Both of the scenarios presented above assume that the assignment of vehicles will be based on the needs of the individual drivers or those of the system as a whole. However it is not unreasonable to assume that society will also wish to minimize the amount of *X* produced on particular segments of the population. The following two sections will illustrate two equity concepts that could be used in traffic assignment.

As an example the people living near major roadways may wish the vehicles to be routed through the network such that the total amount of *X* released on their streets does not exceed some maximum safety standard (i.e., for health reasons). This would correspond to traditional assignment techniques that have an explicit link capacity constraint (3) in which the link capacity is not a function of the amount of vehicles on the link but rather the cumulative amount of pollutant *X* that the vehicles produce on the link. Depending on the method chosen by the authorities for achieving the objective a UE or SO traffic assignment heuristic procedure could be used to model the process. However note that secondary objectives, such as minimizing the number of homes exposed to relatively high levels of *X,* may also be employed, and consequently new assignment techniques could be required.

Last the vehicles may be assigned to a street network in such a way as to ensure that the amount of *X* released on all streets (or a subset of streets) is the same. Under this system equitable (SE) scenario vehicles are routed through the network (on the basis of the routes directly broadcast to the vehicles) such that no one group of people living near the traffic network is affected more than any other group of people. This may at first seem to be an extreme example, but there are currently a number of situations in which traffic control devices are operated such that the negative externalities of traffic (i.e., noise) are "distributed" as evenly as possible among competing routes.

It should be pointed out that although there is a wide range of equity definitions (4) in this paper, only the SE concept defined above will be used. It is also important to stress the fact that in the preceding two types of assignments it is the objectives of the people living near the roadway and not those of the individual drivers or system operators that are of paramount importance.

TRAFFIC ASSIGNMENT BASED ON ENVIRONMENTAL AND EQUITY OBJECTIVES

Until recently the above differentiation and the following examples would be of more academic rather than practical interest. The advent of the in-vehicle RGS, however, has created the potential to change people's route selection behaviors, either directly (explicit directions) or indirectly (variable user charges). Given the demand by the public to reduce pollution it is very reasonable to assume that environmental objectives may be increasingly important in the traffic assignment process. The following sections will examine the potential effects that different objectives could have with a sample test network and a network representing Ottawa, Ontario, Canada, serving as examples.

Carbon Monoxide (CO) Emissions

There are a number of fuel consumption-pollutant emission models of various complexities. For the analyses performed in this paper a macroscopic relationship used in the TRANSYT 7-F model was adopted (5). The general function of the model is

$$ROP = \frac{Ae^{Bv}}{Cv} \qquad \textbf{(1)}$$

where

ROP	=	rate of production [fuel (gal-vehicle/ft) or pollutant (g-vehicle/ft)],
v	=	average vehicular velocity on link (ft/sec), and
A, B, and C	=	constants.

It is assumed that the velocities of the vehicles are constant along each link and the grades on all roads are 0 percent. The velocity on the link is derived by dividing the distance of the link by the travel time. The total amount of pollutant produced per vehicle on any given link is then calculated by multiplying the production rate by the distance of the link.

Equation 1 is applicable for estimating fuel consumption. CO emissions, hydrocarbon emissions, and nitrogen oxide emissions. It was decided that traffic assignment would be examined only on the basis of CO emission rates. There are two reasons for this. The first is that because of the similarity in the form of the production functions the assignment results obtained on the basis of all the pollutants would be similar. The second is that CO is generally considered one of the most critical pollutants where levels need to be reduced (6). The form of the CO production function used in the analysis is given in Equation 2:

$$ROP = 3.3963 \frac{e^{0.014561v}}{1{,}000v} \quad \textbf{(2)}$$

where ROP is the rate of production of CO (g-vehicle/ft), and *v* is the average vehicular velocity on link (ft/sec).

Traffic Assignment with Environmental Objectives: Sample Network

To examine the concepts discussed above it is first useful to examine the changes in link flows when assigning the vehicles on the basis of travel time and CO emissions for an example network. The sample network consists of two links and two nodes, as illustrated in Figure 1. The origin-destination (0-D) demand consists of 8,000 vehicles/hr that travel from node 1 to node 2. There are two potential routes for these vehicles. The first, Route 1, is a two-lane freeway route that is 2000 m long, has a free-flow speed of 100 km/hr, and a capacity of 2,000 vehicles/hr/lane. The second, Route 2, is a shorter two-lane arterial route that is 1,000 m long, but with a lower free-flow travel speed of 60 km/hr and the same lane capacity as that of Route 1.

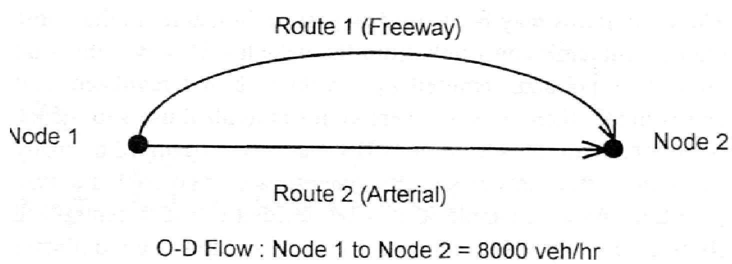

FIGURE 1 Sample network.

In the paper the acronym UE-TT refers to a user equilibrium traffic assignment based on travel time, whereas the acronym SO-TT refers to a system optimal traffic assignment based on travel time. Similarly UE-CO refers to a user equilibrium traffic assignment based on CO emissions, and SO-CO refers to a system optimal assignment based on CO emissions.

For the sample network a UE-TT assignment results in a flow on Route 1 of 5,090 vehicles/hr and a flow on Route 2 of 2,910 vehicles/hr. The travel time on both routes is 100.3 see, and the total travel time on the network is 229.9 vehicle hr. If a traffic operations engineer was able to assign the vehicles to the networks to minimize total system travel time (SO-TT). The flow on Route 1 would increase to 5,218.2 vehicles/hr and the flow on Route 2 would decrease to 2,781.8 vehicles/hr. This would reduce the total system travel time to 222.1 hr.

Figure 2 illustrates the relationship between CO emissions on both routes of the sample problem as a function of flow on Route 1. It can be seen from Figure 2 that if the objective is to minimize the total CO emissions (SO-CO assignment) then 5,161 vehicles would take Route 1, which would result in 6.09 kg of CO being emitted into the atmosphere per hr. This is shown as point a on Figure 2. The rate of CO emitted by each of the vehicles on Route 1 is 0.88 g/vehicle, and on Route 2 it is 0.54 g/vehicle, which is a difference of approximately 40 percent. In total Route 1 receives 1.54 kg of CO, whereas Route 2 receives 4.55 kg, or approximately three times as much.

The difference between the flows from the SO-TT and UE-TT solutions and the SO-CO solution is on the order of 1 percent.

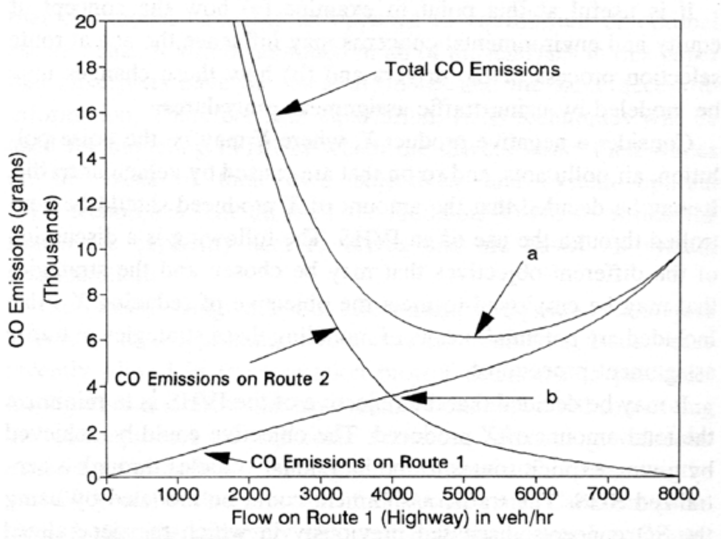

FIGURE 2 CO emissions versus volume on Route 1.

This is also confirmed by the fact that the travel time on Route 1 is 101.9 see and on Route 2 it is 96.5 sec. Therefore for this simple example the UE-TT solution is roughly equivalent to an SO-CO assignment.

If the objective of the assignment is to ensure that both routes have equal CO emission levels (SE assignment) then 3,982 vehicles would be assigned to Route 1 and 4,018 vehicles would be assigned to Route 2. This assignment is shown as point b on Figure 2. The difference in route flows between the SE and the SO-CO solutions is on the order of 25 percent. The change in route flows would increase the total CO emitted by 14 percent, to 7.10 kg/hr, in which each route experiences an emission rate of 3.55 kg/hr. The travel time on Route 1 is 82.6 see, and the travel time on Route 2 is 206.5 sec. Therefore unless the drivers are explicitly assigned to the network in the proportions given above this would be an unstable solution.

Figure 3 illustrates the amount of CO produced per vehicle as a function of the flow on Route 1. If the vehicles were allowed to choose their own route but were charged for CO emissions (and considered only the cost of this in their route selection process) then 3,966 vehicles would take Route 1 and 4,034 vehicles would take Route 2. The UE-CO solution is illustrated by point a in Figure 3, in which it may be seen that the vehicles on both routes emit 0.89 g/vehicle. The travel time on Route 1 is 82.43 see, and the travel time on Route 2 is 209 seconds.

It may be seen from the above analysis that the SE and UE solutions on the basis of CO emissions have similar results in terms of route volumes. The primary difference (aside from the objectives) between the two is that in the SE assignment it is assumed that the drivers have routes chosen for them whereas in the UE assignment the drivers select their own routes on the basis of the amount of CO they produce. This indicates that charging vehicles for pollutant emissions could achieve the same equitable environmental goals as routing them by using a centralized RGS. The negative side to this strategy is that charging for use of the road on the basis of environmental concerns could actually increase the total amount of CO produced.

It may also be seen that unlike the SO-TT and UE-TT solutions. the SO-CO and UE-CO solutions are significantly different. Therefore when IVHS strategies are implemented the objectives adopted could have a significant impact on the link flows and the amount of pollution produced. The following sections will examine whether these findings hold true for more realistic networks.

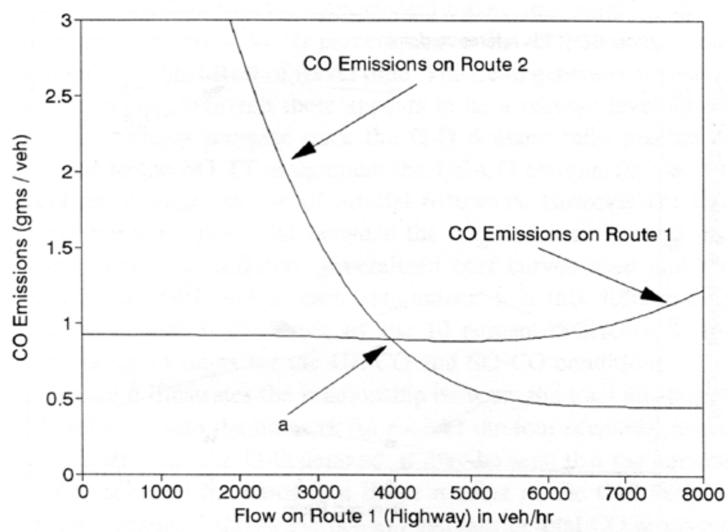

FIGURE 3 Route CO emission rates versus volume on Route 1.

Traffic Assignment with Environmental Objectives: Ottawa Network

A network from Ottawa, Ontario, Canada was chosen as a test bed to examine if the trends that were found for the simple example also exist in larger networks. The Ottawa network consists of 1,402 links, 646 nodes, and 67 zones. It is linear in shape, with the Queensway, the major highway in Ottawa, running in an eastwest direction through the center of the city. The assumptions and relationships that were used in the sample analysis are also used in the Ottawa analysis.

Six O-D demand rates were used in the traffic assignment analysis to identify any demand-related trends. The percentage of trips for each O-D pair was kept constant, and only the total number of trips was varied. Table 1 lists the scale factors and the corresponding weighted average volume-to-capacity (*v/c*) ratio on the network for a UE traffic assignment based on travel time. The weighted average v/c ratio is the average volume-to-capacity ratio on all links weighted by the number of vehicles on the link. The first demand rate, with a scale factor of 1, represents a lightly loaded network, as illustrated by an average weighted *v/c* ratio of 0.19. When the scale factor is increased to 6, the average *v/c* ratio increases to 0.91.

TABLE 1 Key to Demand Rates

Demand Rate	Average Link
1	0.19
2	0.33
3	0.49
4	0.62
5	0.78
6	0.91

Traffic Assignment Based on Environmental Objectives on Large Networks

Common assignment techniques such as the Frank-Wolfe algorithm and the method of successive averages algorithm lend themselves well to traffic assignment based on environmental objectives. As discussed above all that is required is a link cost function based on CO production instead of one based on travel time.

Traffic assignments based on UE (travel time), SO (travel time), UE (CO production), and SO (CO production) were performed by using the ASSIGN traffic assignment model (7) on the Ottawa network. Both the Frank-Wolfe algorithm and the method of successive averages algorithm were used, and both gave approximately equivalent results. The solutions presented in this paper were derived by using the former algorithm. In every case the traffic assignment results based on environmental objectives and obtained by using Equation 2 as the link cost function met the underlying objective to minimize CO production. In the case of UE-CO the levels of CO production on all of the used routes for a given O-D were equal, and there were no routes that had lower levels of CO production. For the SO-CO examples the marginal CO production rates on all used routes were equal, and no unused route had lower marginal CO production rates. In addition the total amount of CO produced decreased with each iteration of the algorithm and converged toward one value.

However some theoretical problems associated with using Equation 2 should be pointed out. It may be seen in Figure 3 that on Route 1 (the highway) the CO emissions per vehicle decrease as volume increases, reach a minimum, and then increase after that. This pattern is typical of pollution models in general because pollution levels tend to be highly correlated with fuel consumption. Fuel consumption is typically modeled as a function of speed, with some minimum rate occurring at an optimal speed that is typically in the range of 45 to 55 mph. For speeds on either side of the optimal speed fuel consumption increases at an increasing rate. As the volume on the link increases the speed decreases. This results in lower fuel consumption and hence lower CO emissions. Eventually the average speed decreases past the 11 optimal" velocity and the CO emissions begin to rise. This is illustrated by the convex shape of the CO production function for Route 1 in Figure 3. Note that the arterial link does not follow this pattern but father increases with all volumes. This is because for this link the vehicles always travel below the "optimal" velocity because of speed limit constraints.

It is a well-known fact that the generalized cost functions used in UE and SO traffic assignments must be positive and must increase with volume (8). When they do not there is no guarantee that the resulting UE or SO program will have a unique minimum point. There are two important points relating to this last statement. The first is that the solution found by using the Frank-Wolfe algorithm may not be a global minimum but rather only a local minimum. The second point is that there is no guarantee that the link flows that are identified are unique. From a SO-CO perspective this is not overly critical in that in this paper the authors are only interested in system CO production and total travel time. Therefore at worst the SO-CO solutions are a conservative estimate, and theoretically there could be a "better" solution. However from a UE-CO perspective the results could be more subtle. Theoretically there could be an alternative set of link flows that results in the same or a smaller value of the objective function but that has lower (or higher) aggregate CO values than those reported in this paper.

It should be pointed out that when the conditions for a unique minimum (link cost function increasing and positive) are violated it does not automatically indicate that the resulting solution will not be a global minimum or unique. This is especially true for the examples used in this paper, in which the cost function decreases only marginally with travel time before increasing once the "optimal" velocity is reached. The fact that all of the environmental assignment solutions met the underlying objectives, as discussed earlier, was taken as an internal consistency check that the results presented in the following section are acceptable.

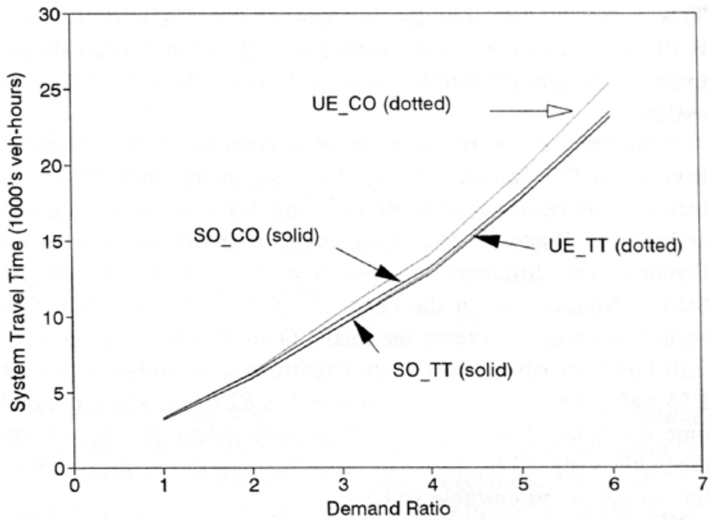

FIGURE 4 System travel time versus O-D demand ratio.

Ottawa Network Results

Figure 4 shows the system travel time results for each of the four traffic assignment scenarios as a function of the O-D demand ratio used. A number of trends are present that would be expected given past research in the area and general knowledge of macroscopic traffic assignment models.

These include the following:

1. As the demand increases the total system travel time also increases and at a slightly increasing rate for all four assignment scenarios.
2. The total system travel time is lowest for the SO assignment based on travel time.
3. The UE solution based on travel time is very similar to that for the SO assignment based on travel time.

As in the sample problem, the UE-CO solution produced similar (although slightly higher) total system travel time results compared with those produced by the UE-TT and SO-TT solutions. In addition, the SO-CO assignment produced the worst results with respect to total travel time on the system.

Figure 5 was created to better illustrate the differences between the various scenarios. Figure 5 illustrates the percent increase in system travel time for each traffic assignment scenario compared with the system travel time for the SO assignment based on travel time (i.e., the assignment with the lowest system travel time for a given demand level). The latter traffic assignment, SO-T-r, is therefore represented in Figure 5 by a straight-line function that is equal to zero. It should also be noted that although the travel time differences are not huge (i.e., <10 percent) the maximum amount of system travel time savings that may be achieved through IVHSs is usually considered to be in the range of 5 to 10 percent (9).

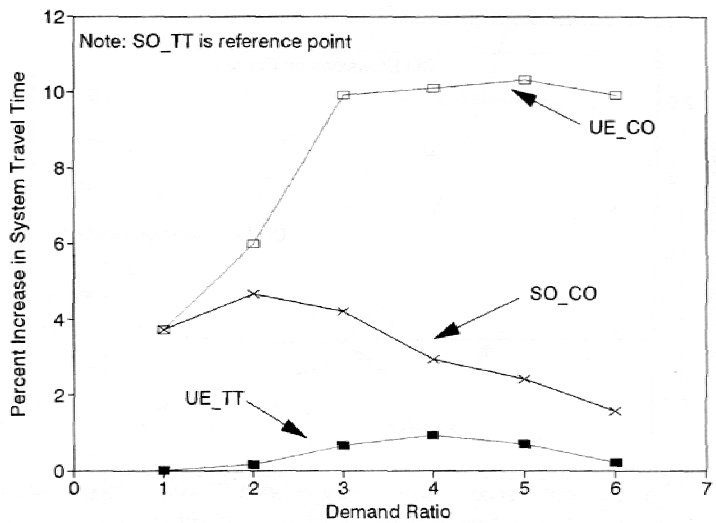

FIGURE 5 Percent increase in system travel time versus O-D demand ratio.

It may be seen in Figure 5 that the difference in the SO-TT and UE-TT solutions are minimal. However the relationship is concave, with the biggest difference, on the order of 1 percent, occurring at the middle demand levels. This may be explained by the fact that at low and high demand levels there is not as much route choice for the vehicles because the link travel times are not affected by their individual decisions. For example at low O-D demand levels every vehicle is basically assigned to the minimum path route that, because of the low volumes, does not Experience an appreciable rise in travel time. At high demand levels the results are more subtle. The link flows on the highways based on the UE-TT assignment are on average about 5 percent higher than those based on the SO-TT assignment. However because of the nature of the travel time function this difference in link flows results in only a marginal difference in aggregate travel time.

When the traffic is assigned to the network with the objective of an SO-CO assignment the total system travel time is on the order of 1.5 to 4 percent higher than that observed for an SO-TT assignment. In general as the demand rate increases this difference decreases. The link flows for the SO-CO assignment tended to be more similar to those for the UE-TT assignment, in which more vehicles are assigned to the highways than by the SO-TT assignment. This makes intuitive sense in that the link pollution-volume curve is relatively flat for highways, and therefore adding volume to highways does not appreciably raise pollution levels as much as adding vehicles to arterial roadways. On the basis of the results from Figure 5 it may be seen that for congested networks if policies were implemented to reduce overall CO emissions the actual amount of travel time in the system would increase on the order of 2 percent.

If the drivers were allowed to choose their routes individually and their decisions were based solely on the amount of CO produced (EU-CO), then the total system travel time would increase by approximately 4 to 10 percent above that if the drivers considered only the effect of travel time. The trend generally increases with demand, although there appears to be a relative leveling off at a 10 percent increase once the O-D demand ratio reaches 3. Similar to the SO-TT assignment the UE-CO assignment also favors on average the use of arterial roadways. However the link flows are very dissimilar between the two assignments, and this results from the different generalized cost curves used and the underlying objectives in each assignment. It is this difference in link flows that is illustrated by the 10 percent difference in aggregate travel times

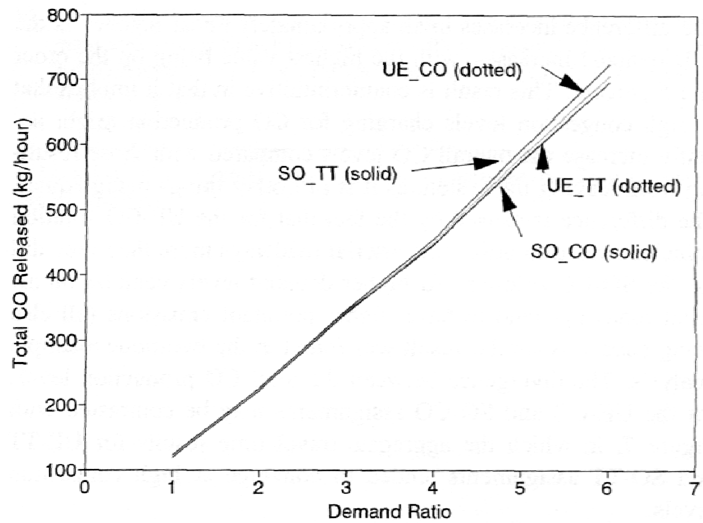

FIGURE 6 CO production versus O-D demand ratio.

for the UE-CO and SO-CO conditions.

Figure 6 illustrates the relationship between the total amount of CO released into the network for each of the four scenarios tested as a function of the O-D demand. It may be seen that the amount of CO released increases in a linear manner as the O-D rate increases. Figure 7 shows the percent increase in total CO produced for each scenario compared with that produced from the SO traffic assignment based on CO considerations (the lowest for a given demand level). The latter traffic assignment is therefore represented by a straight-line function that is equal to zero.

It may be seen that for high demand levels the UE-TT assignment results in CO output very similar to that from the SO assignment, which seeks to minimize this value (SO-CO). However at lower demand levels the difference in CO output can be on the order of 2.5 percent. This implies that in congested networks the UE-TT objective (i.e., what currently occurs) results in CO production levels that are approximately equivalent to what could be achieved if vehicles were directly routed through the network on the basis of minimizing CO production. As stated previously this is due to the similarities in link flows, in which in both cases the highways generally experienced higher volumes.

The opposite trend occurs for the UE-CO assignment when the drivers are taxed on the amount of CO that their vehicles produce and the drivers choose their routes solely to minimize this cost. At low demand levels the difference in CO emissions is minimal.

The difference increases in an approximately linear manner as the O-D demand increases, with the highest value being on the order of 1.5 percent. This result is counterintuitive in that it implies that at high congestion levels charging for CO production might actually increase the overall CO levels compared with those resulting from leaving the system as it is (all other things being equal). The difference is caused by the feet that for the UE-CO solution vehicles tended to utilize the arterial roadways more than they did for the SO-CO solution. At higher demand levels vehicles on arterial roadways tend to have higher pollutant emissions (all else being equal). A similar result was found in the two-node example analysis. The divergence between the total CO production levels for the UE-CO and SO-CO assignments may be contrasted with Figure 7. in which the aggregate travel time results for UE-TT and SO-TT assignments tended to converge at high congestion levels.

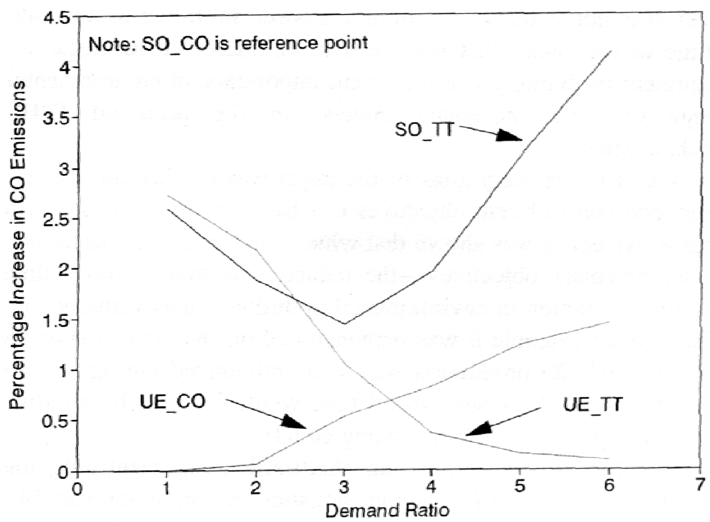

FIGURE 7 Percent increase in CO production versus O-D demand ratio.

In terms of total CO production the SO-TT assignment has the largest difference compared with the SO-CO assignment. The relationship is convex. with the difference first decreasing as demand increases until the demand ratio is 3 and increasing after that. The minimum difference is 1.5 percent, and the largest is approximately. 4 percent, which occurs at the demand ratio of 6. Again this pattern is a result of the fact that in the SO-TT assignment the arterial roadways tend to have higher link volumes than the SO-CO assignment at high congestion levels. The results shown in Figure 7 imply that if an RGS was instituted with the sole purpose of minimizing travel time, other important objectives, such as reducing CO levels, might actually become worse.

CONCLUDING REMARKS

It can often be dangerous to generalize the results of macroscopic traffic assignment models to actual traffic systems. This would be especially. true in this analysis, in which many simplifying assumptions are made (i.e., 100 percent homogeneous driver and vehicle populations) and very simple production functions are used (i.e.. Bureau of Public Roads travel time function and TRANSYT CO emission function). Perhaps more importantly vehicle emissions were assumed to occur uniformly along the length of the link rather than to have higher concentrations at the intersections, where traffic often stops. The intent of this paper, however, was not to derive a definitive answer but rather to illustrate some of the issues that will need to be addressed in traffic assignment modeling given the recent importance of environmental objectives and increasing interest in the proposed IVHS technologies.

One of the primary aims of the paper was to illustrate the importance that different objectives can have on the operation of a traffic system. It was shown that what would intuitively seem like complementary objectives-the reduction in system travel time and the reduction in environmental pollution-may actually conflict. As an example it was demonstrated on the Ottawa network that if total CO production was to be minimized during periods of congestion the system travel time would increase by approximately 2 percent (all things being equal),

Therefore it is very important that traffic assignment programs produce comprehensive output statistics of important variables such as travel time, pollutant emissions, and noise levels to enable transportation professionals to study any trade-offs that may be required. Related to this task is the fact that appropriate production functions need to be identified for these negative externalities that relate the important link attributes (travel time, stop time) to the amounts of pollutants produced. Traffic engineers need to adopt a more sophisticated generalized cost function that has a wide range of important parameters as opposed to one that is based solely on travel time. This may not be as straightforward as it appears because not only will the pollutants have different weights but these weights may be a function of the amounts of pollutants produced. For example a doubling of CO levels on a link may result in a quadrupling of importance of the CO level in the generalized cost function because of a nonlinear relationship between CO level and general health. In addition the generalized cost function may not strictly increase as a function of flow when pollution costs are involved. This could result in the need to develop assignment techniques different from those that have historically been used.

The second point that is raised in this paper is that there is a definite need to expand traffic assignment techniques to account for change-, in system objectives and changing technologies. To a certain extent this has been done (1-3,10) with respect to evaluating IVHS operations. However to date there does not appear to be any assignment models that assign traffic on the basis of an equity-as opposed to an equilibrium-objective function. As was demonstrated in the two-node network problem, there is a definite need to examine the effects that equitable objectives could have on traffic networks and whether there might be other methods of achieving the same results. For example it was demonstrated on the sample network that different techniques may be used to achieve the same goal. The CO emissions analysis showed that charging drivers for their individual production of CO and letting them make their own decisions (UE assignment) gave results equivalent to those of explicitly routing the drivers on the basis of considerations (SE assignment). Of course whether any of these patterns will hold for larger, more complex networks and for more realistic traffic assignment models needs to be studied.

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