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16. ABSTRACT Most of the existing dynamic traffic assignment methodologies, which have been predominately travel time based, are not appropriate for use in a traffic network analysis where the environmental concerns prevail. The primary reason for this is that the travel time variables and the environmental variables, which include but are not limited to fuel consumption, vehicle emissions and traffic noise, have different sensitivities to the distribution of the vehicle's modal events. Therefore, the travel time based and the environmental based dynamic traffic assignments should virtually result in different dynamic network flows and queues. This research presents a new approach that attempts to explicitly incorporate the multiple transportation objectives into the dynamic traffic assignment/simulation model. The dynamic traffic assignment/simulation method, instead of the static traffic assignment method, is selected in the proposed approach in order to correctly identify the time series of vehicles' modal events, and therefore to more accurately estimate the impacts of alternative traffic and control scenarios on various travel time and environmental factors. Since the research proposes a set of new environmental based traffic assignment principles, the dynamic traffic loading can therefore be explicitly environmental based. Consider a real traffic network where the drivers strive to select the paths for travel. Most drivers are unlikely, in reality, to choose the paths based on the explicit environmental considerations. With the applications and the deployment of Advanced Traveler Information Systems and Road Congestion Pricing mechanisms, however, the traffic routing which is strictly based on a selected environmental objective is not unrealistic in the foreseeable future.			
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**New Technologies and Methodologies for Evaluating
and Analyzing the Implications of Various New
Transportation Objectives**

**Lei Yu
and
Naomi W. Ledé**

**Center for Transportation Training and Research
Texas Southern University
3100 Cleburne Avenue, Houston, TX 77004
Tel: (713) 313-1841 Fax: (713) 313-1856**

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ABSTRACT

Most of the existing dynamic traffic assignment methodologies, which have been predominantly travel time based, are not appropriate for use in a traffic network analysis where the environmental concerns prevail. The primary reason for this is that the travel time variables and the environmental variables, which include but are not limited to fuel consumption, vehicle emissions and traffic noise, have different sensitivities to the distribution of the vehicle's modal events. Therefore, the travel time based and the environmental based dynamic traffic assignments should virtually result in different dynamic network flows and queues.

This research presents a new approach that attempts to explicitly incorporate the multiple transportation objectives into the dynamic traffic assignment/simulation model. The dynamic traffic assignment/simulation method, instead of the static traffic assignment method, is selected in the proposed approach in order to correctly identify the time series of vehicle's modal events, and therefore to more accurately estimate the impacts of alternative traffic and control scenarios on various travel time and environmental factors. Since the research proposes a set of new environmental based traffic assignment principles, the dynamic traffic loading can therefore be explicitly environmental based. Consider a real traffic network where the drivers strive to select the paths for travel. Most drivers are unlikely, in reality, to choose the paths based on the explicit environmental considerations. With the applications and the deployment of Advanced Traveler Information Systems and Road Congestion Pricing mechanisms, however, the traffic routing which is strictly based on a selected environmental objective is not unrealistic in the foreseeable future.

Key Words: Environmental Objective, Dynamic Assignment, Traffic Simulation

EXECUTIVE SUMMARY

In order to reach the goals set by the Clean Air Act Amendments (CAAA) of 1990 and the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, nation wide transportation professionals are actively searching for effective measures aimed at minimizing the effects of vehicle pollutant emissions. Some of the example measures for reducing vehicle emissions include Employee Trip Reduction Programs, Ridersharing Strategies with Vanpools and Carpools, and the use of alternative fuels. The effectiveness of these measures and the corresponding cost-benefit analyses, however, have not been extensively and quantitatively conducted.

There exists a traditional perception in the transportation community which suggests that a successful transportation project and an effective traffic control and management strategy for relieving traffic congestion and reducing travelers' trip travel times will automatically result in the minimum fuel consumption and vehicle emissions. The research by Yu and Stewart (1995), however, has shown that this perception is not correct. The reason for this is that the magnitudes of the fuel consumption and emissions are heavily affected by the distribution of vehicles' modal events, which are acceleration, deceleration, cruise and idle, while the travel time based factors are mainly dominated by each link's average speed. This finding indicates that the transportation planners and engineers have to more explicitly and quantitatively consider the environmental factors when evaluating various alternative transportation projects and programs and determining the traffic control and management strategies.

This research develops a methodology that can be used to evaluate the traffic control and management strategies explicitly from a consideration of multiple transportation objectives including the new environmental factors. This goal will be achieved by incorporating the multiple transportation objectives including various environmental variables into a dynamic traffic assignment/simulation approach. The selected dynamic traffic assignment approach can quantitatively estimate the distribution of vehicles' modal events including acceleration, deceleration, cruise and idle, which can then be used for estimating the amounts of fuel consumption and emissions. The new multiple objective based dynamic traffic assignment methodology can search for the optimum solutions to the congested traffic network based on the dynamic user time equilibrium, the total system travel time, the total fuel consumption and the vehicle emission objectives.

Multiple Transportation Objectives

Five major transportation objectives are identified in this research, which are user time equilibrium, system travel time, fuel consumption, vehicle emission and traffic noise. The objective of vehicle emissions can be further classified into three major emission components, namely carbon monoxide (CO), hydrocarbon (HC) and oxides of nitrogen (NOx).

User Time Equilibrium

The user time equilibrium objective can be described by Wardrop's first assignment principle (Wardrop, 1952), which states that drivers behave in the route selections to minimize their own travel times. The traffic assignment based on the user time equilibrium objective results in a traffic loading where all used paths have equal travel times, which are less than or equal to all unused paths. The user time equilibrium represents a realistic and spontaneous behavior of drivers in making their route choice decisions.

System Travel Times

The system travel time objective represents Wardrop's second assignment principle (Wardrop, 1952) which states that drivers behave to minimize the total network wide travel times in selecting their paths. The minimization of total system travel times results in a scenario where some drivers may elect to take longer travel time routes in order for other drivers to reduce their travel times more significantly. The system time optimal is a more ideal objective and can only be realized through the system control and management, for example, through the applications of Route Guidance Systems.

Fuel Consumption

The fuel consumption objective is to save energy, which is not an unlimited resource on the earth. While the automobile industry strives to reduce the fuel consumption index through improvements in the internal design and structure of engines and vehicles, using traffic control and management methods to save energy is a new issue in transportation. The fuel consumption is of great importance to the environment and general public, because it is closely related to vehicle emissions.

Vehicle Emissions

The reduction of vehicle emissions, which are pollutants emitted from automobile fuel, is an objective that helps clean the air pollution. The pollutants emitted from the vehicles are of concern to the public, as they are a direct cause of numerous human ailments and health problems including pulmonary complaints, cancer, and vision problems. Among all of the automobile emitted pollutants, CO, HC and NO_x are the most significant species that pollute environments and influence public health.

Traffic Noise

The reduction of traffic noise is an objective that strives to minimize the effects of the unwanted and accumulated vehicle sounds. The problem of noise impact from traffic is unique in its spontaneity and lack of duration. Traffic noise, unlike other pollutants, leaves no residual evidence to serve as a continuing reminder of its unpleasantness. However, it is a major source of irritation and discomfort. Traffic noise factor is equally important as other environmental factors, but it will not be discussed further in this research. Alternatively, it will be researched in a separate work.

Outline of the Proposed Method

The proposed approach in this research used the dynamic traffic assignment/simulation procedure, which was initially described by Yu, et al. (1993). A subroutine for dealing with the environmental consideration, however, are incorporated in this research. The original dynamic assignment/simulation method was a mesoscopic approach which attempts to achieve either an actual time anticipatory user equilibrium or a system time optimal solution. The approach was designed as a discrete-time dynamic assignment approach, which discretized the entire analysis time period into a number of shorter time slices. The length of each time slice could be either relatively short or long depending on the variability of the traffic conditions and the overall analysis purposes/objectives.

The dynamic assignment approach uses vehicle packets as the basic units in the traffic lading process. The traffic demands within each time slice for an OD pair are organized onto a

number of packets. The size of a vehicle packet is determined depending on how many incremental steps one desires to use in assigning the entire traffic demand that departs for a given OD during a given time slice. For example, when the departure traffic demand rate is 1,000 veh/hr during a given time slice, and the time slice length is 10 minutes, the packet size will be 16.67 vehicles if 10 incremental steps are required $(1,000 * (10/60) / 10)$. The fact that the packet size is a function of the user specified incremental size indicates that this packet size will automatically be different for different analysis time slice duration. For example, if the traffic demand for another 10 minute time slice was 1,200 veh/hr, the packet size for that time slice would become 20 vehicles $(1,200 * (10/60) / 10)$. It can be noted from the above example that a packet size is neither constant, nor required to be an integer.

The Numerical Example

The geometric layout of the hypothetical network is shown in Figure E-1. This network contains 5 nodes and 5 links. Node 1 - 3 are assumed to be the sources where the trips generate and sink. Node 4 is a signal controlled intersection, while Node 5 is a non-signal controlled intermediate node. All the links in the network are given the identical characteristics and capacities, in which the link length is assigned a value of 2 kilometers, the free flow speed is given 60 kilometers per hour with a single lane. The analysis time slice length will be fixed to 2 minutes for all scenarios.

Incident Scenario

The scenario assumes that a travel demand of 2000 vehicles per hour from Node 1 to Node 2 lasts exactly one hour. No trips are assumed to travel from Node 3 and therefore the traffic signal at Node 4 is made to assign the 100% of its cycle time to Link 3 for the trips traveling from Node 1 to Node 2. A traffic incident occurs at the downstream end of Link 3 during 20-40 minute period which blocks 80% of the link capacity. The majority delays and the stops in the network will be caused by the traffic incident.

The proposed assignment approach is implemented based on 7 different objectives, namely user time equilibrium, system travel time, total fuel consumption, total vehicle emission, CO

emission, HC emission and NOx emission. The total system travel time, fuel consumption and vehicle emission are then estimated from the outputs of each run of the dynamic assignment.

Figure E-2 illustrates the total system travel time and the total fuel consumption resulted from each implementation of the proposed approach. It is shown that the user time equilibrium based assignment resulted in the highest total travel time, while the system time based assignment resulted in the lowest total travel time. In addition, both user time equilibrium based and system time based assignments resulted in high fuel consumption, which implicates that none of the travel time based assignments can be used as approximation to the fuel consumption based assignment. It is also shown, from the same graph, that both consumption based and emission based assignments resulted in similar total travel time and fuel consumption, although the consumption based assignment resulted in the lowest fuel consumption.

Figure E-3 illustrates the total fuel emission values, which were obtained from each implementation of the proposed approach. The user time equilibrium objective resulted in the highest values for all kinds of emissions and the system time objective resulted in higher emissions than both consumption and emission objectives, which again implicates that the travel time based traffic assignments are not appropriate for use in a situation where vehicle emissions are major concerns. Figure E-3 also shows that the total emission based assignment and the CO emission based assignment resulted in about the same trends in the curves. The magnitudes of the HC and NOx emissions were relatively small, which however does not mean that they are less important pollutant species than the CO emissions.

Signal Scenario

In this particular scenario traffic demands are assumed to come from both Node 1 and Node 3 heading for Node 2. The traffic signal at Node 4 will give 50% of its cycle time, which is set to 120 seconds, to Link 3 and 50% to Link 5. The loss times of the signal for both phases are fixed to 5 seconds. Travel demands from Node 1 and Node 3 are respectively set to 2500 and 500 vehicles per hour for an entire hour period. The delays and stops in this scenario are primarily caused by the red time of the traffic signal.

Figure E-4 illustrates the total travel time and fuel consumption for the network for which the assignment is carried out based on different objectives. Similar to Figure E-2, the user time equilibrium based assignment resulted in the highest system travel time, while the system time based assignment resulted in the highest fuel consumption. In addition, the fuel consumption based and the HC emission based assignment resulted in the identical traffic loading, which incurred equal fuel consumption amount and the total system travel time, which are lower than the other emission objective based assignments.

Figure E-5 illustrates the amount of emissions of each emission species resulted from different assignment implementations. Similar to the observations from Figure E-3, CO emissions take most of the portions of the total emissions. Also, the emissions resulted from the different environmental objective assignments are very close, which implicates that assignment based on one kind of environmental objective may be used as the approximation to any of the other emission based assignments.

All the above graphs represented the comparisons of total travel time, fuel consumption and emission, which were obtained from the implementation of the proposed approach based on different assignment objectives. In reality, since the traffic is assigned to the traffic networks according to the traditional user time equilibrium principle, it is necessary to evaluate the environmental implications of alternative traffic control strategies based on the same user time equilibrium objective. In the particular scenario in this section, an alternative traffic signal timings, which assigns 70% of cycle time to Link 3 and 30% to Link 5, was also applied to the network. The implementation of this new signal control scenario resulted in a reduction of 1552 vehicle-minutes in total travel time, 10 gallons in fuel consumption, 1148 grams in total vehicle emission, 1047 grams in CO emission, 30 grams in HC emission and 71 grams in NOx emission. The proposed approach can, therefore, be used to evaluate the environmental implications of various traffic control and management strategies based on either the same or different objectives.

Conclusions

This report presented an approach, which can perform the dynamic traffic assignment logic based on multiple transportation objectives. The proposed approach can search for the optimal solution of each particular objective and estimate the respective network assignment results. Each particular objective based non-user equilibrium traffic assignment and loading can be eventually realized with the advances and applications of telecommunication technologies, route guidance systems and electronic road pricing. The new approach can be used to evaluate the travel time and environmental implications of alternative traffic control and management strategies.

The example network and traffic scenarios indicated that the travel time based assignments, either by user time equilibrium or system time optimal, are not appropriate for use in a situation where the environmental variables are the major consideration, especially when the queues and delays are present. While all the environmental variables were estimated from the distribution of vehicle's modal events, each particular estimation was shown to be more or less sensitive to each individual modal event. In general, however, it can be concluded that one environmental variable based assignment can be used as the approximate estimation of the others.

The estimation of quantities of the fuel consumption and vehicle emissions were made from a set of selected formulas. It is felt that these formulas should be replaced with more sophisticated models, which can better reflect the sensitivity of each environmental factor to the distribution of the vehicles' modal events.

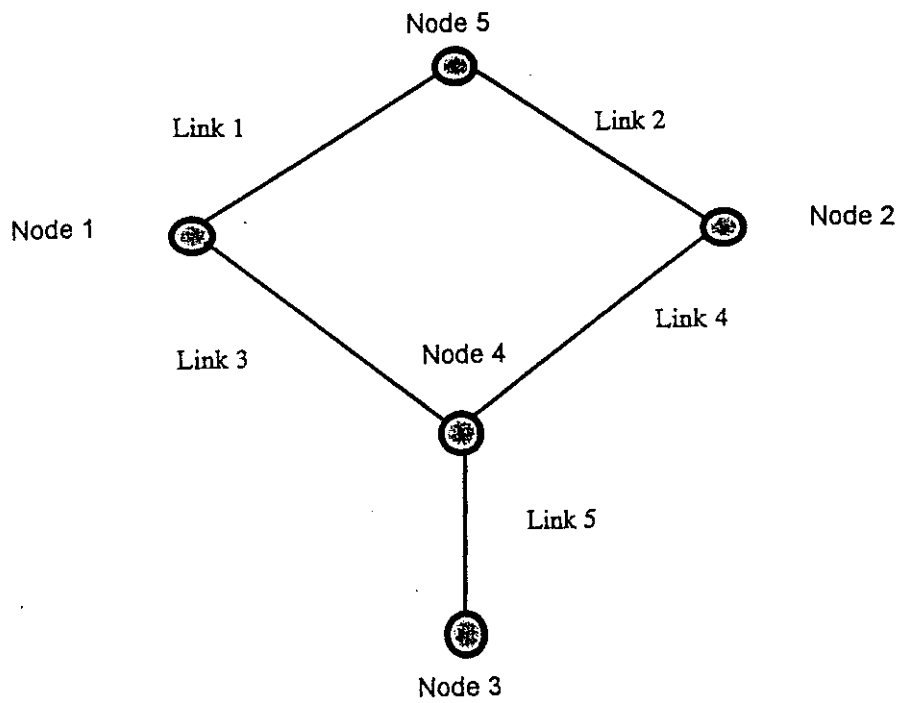


FIGURE E-1: Geometrical Layout of the Hypothetical Traffic Network

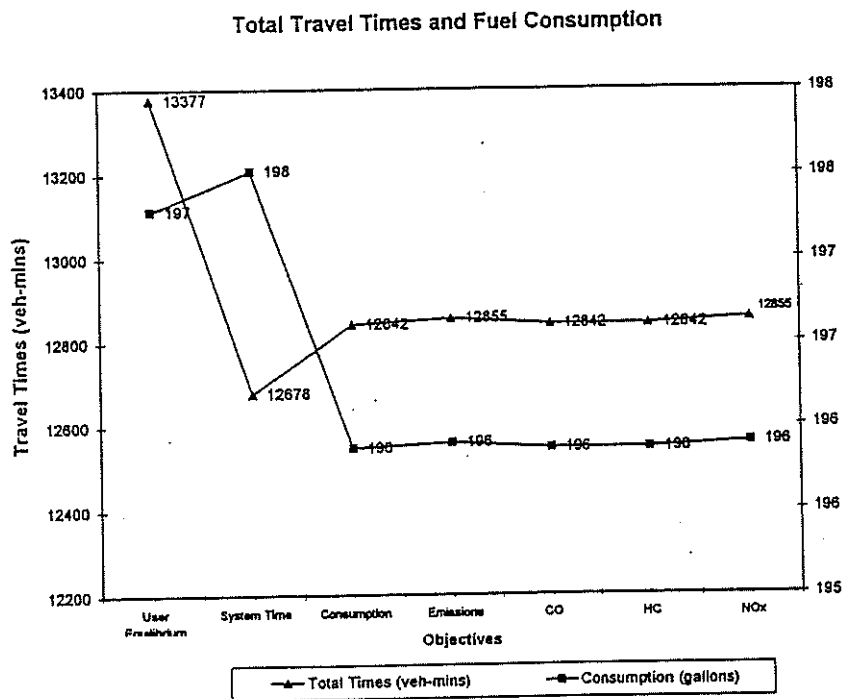


FIGURE E-2: Total Times and Fuel Consumption of the Traffic Assignments Based on Different Objectives for the Traffic Incident Scenario

Fuel Emissions Based on Different Objectives

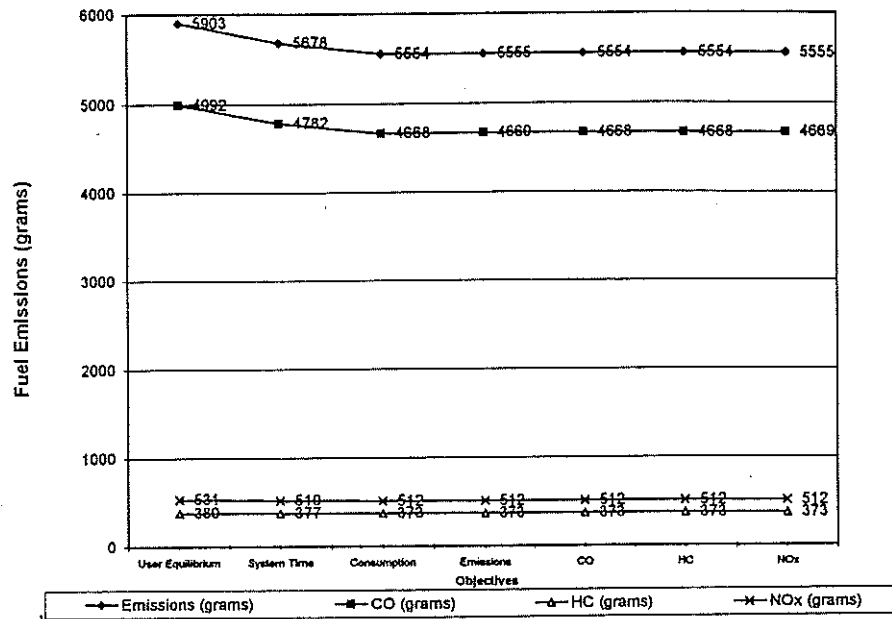


FIGURE E-3: Vehicle Emissions of the Traffic Assignments Based on Different Objectives for the Traffic Incident Scenario

Total Travel Times and Fuel Consumption

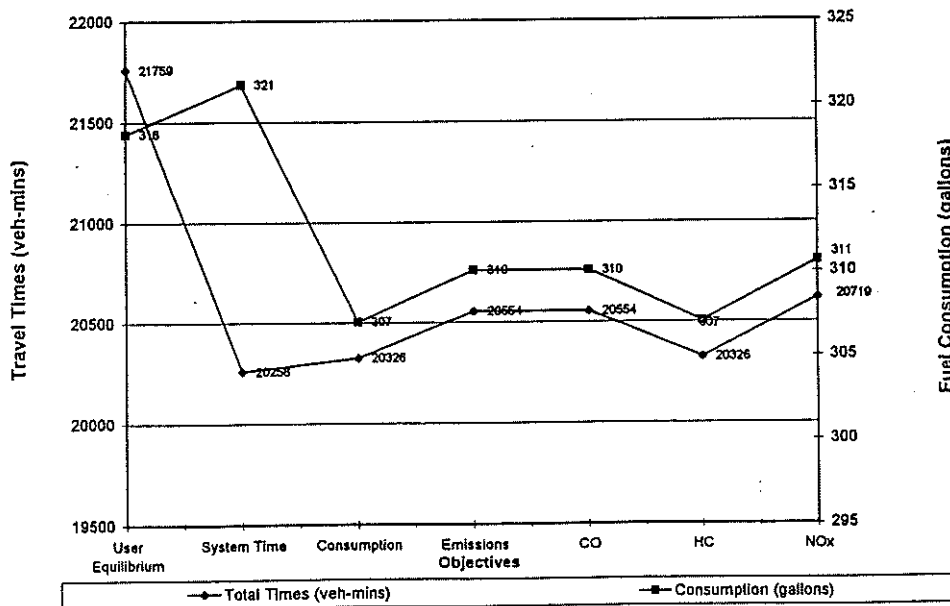


FIGURE E-4: Total Times and Fuel Consumption of the Traffic Assignment Based on Different Objective for the Traffic Signal Scenario

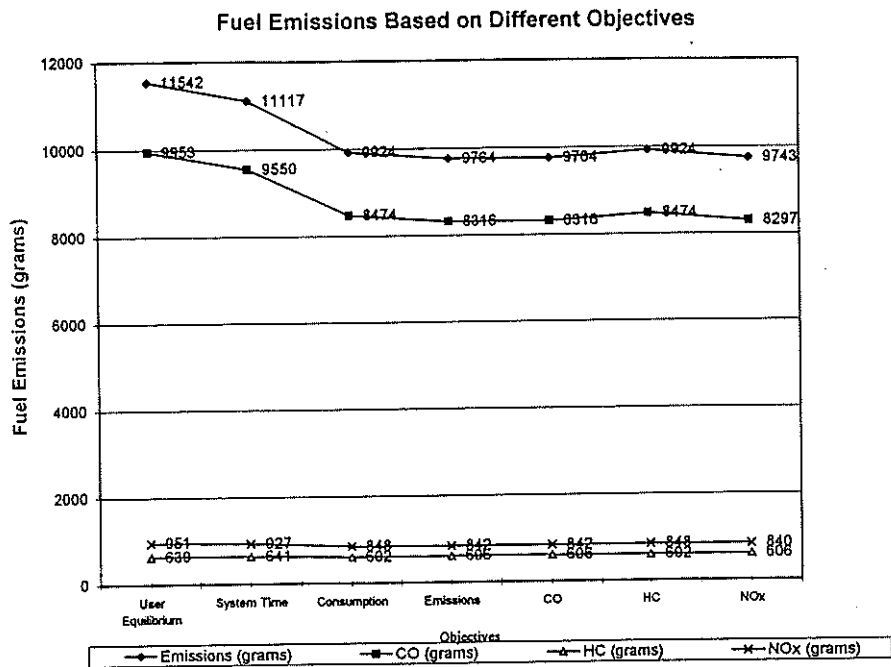


FIGURE E-5: Vehicle Emissions of the Traffic Assignments Based on Different Objectives for the Traffic Signal Scenario

CHAPTER 1

INTRODUCTION

In order to reach the goals set by the Clean Air Act Amendments (CAAA) of 1990 and the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, nation wide transportation professionals are actively searching for effective measures aimed at minimizing the effects of vehicle pollutant emissions. Some of the example measures for reducing vehicle emissions include Employee Trip Reduction Programs, Ridersharing Strategies with Vanpools and Carpools, and the use of alternative fuels. The effectiveness of these measures and the corresponding cost-benefit analyses, however, have not been extensively and quantitatively conducted.

There exists a traditional perception in the transportation community which is that a successful transportation project and an effective traffic control and management strategy for relieving traffic congestion and reducing travelers' trip travel times will automatically result in the minimum fuel consumption and vehicle emissions. The research by Yu and Stewart (1995), however, has shown that this perception is not correct. The reason for this is that the magnitudes of the fuel consumption and emissions are heavily affected by the distribution of vehicles' modal events, which are acceleration, deceleration, cruise and idle, while the travel time based factors are mainly dominated by each link's average speed. This finding indicates that the transportation planners and engineers have to more explicitly and quantitatively consider the environmental factors when evaluating various alternative transportation projects and programs and determining the traffic control and management strategies.

This research is an effort that attempts to develop a methodology that can be used to evaluate the traffic control and management strategies explicitly from a consideration of multiple transportation objectives including the environmental factors. This goal will be achieved by incorporating the multiple transportation objectives including various environmental variables into a dynamic traffic assignment/simulation approach. The selected dynamic traffic assignment approach can quantitatively estimate the distribution of vehicle's

modal events including acceleration, deceleration, cruise and idle, which can then be used for estimating the amounts of fuel consumption and emissions. The new multiple objective based dynamic traffic assignment methodology can search for the optimum solutions to the congested traffic network based on the dynamic user time equilibrium, the total system travel time, the total fuel consumption and the vehicle emission objectives.

For decades, the drivers' route choice behavior has been described by the Wardrop's (1952) first user equilibrium principle. While the assignment based on the other criteria, for example the environmental criteria, cannot perceivably be realized by drivers' voluntary behavior, the rapid development of computer and telecommunication technologies has significantly increased the potential for routing vehicles based on non-user-equilibrium objectives. Especially the field experiments of Route Guidance Systems and applications of Electronic Road Pricing systems provide an unique opportunity for transportation engineers to intentionally and purposely influence drivers' route choice decisions (Dawson, 1985). Therefore, with the further advances of various ITS related technologies, traffic routing based on non-user equilibrium is not unrealistic.

To describe and examine the proposed approach, the remainder of this report is organized as follows. Following this introduction section, the various new transportation objectives will be briefly discussed in Chapter 2 including how these variables should be calculated for a dynamic network. Chapter 3 will primarily describe the proposed approach that incorporates the multiple transportation objectives into the selected dynamic traffic assignment/simulation model. Specifically, the proposed assignment principles based on the environmental criteria will be first presented and the assignment procedures based on various new objectives are then described. Chapter 4 will use a hypothetical traffic network to examine the proposed approach with two traffic and control scenarios. Finally, the report is concluded by a summary in Chapter 5 and a recommendation for further research is provided in the same chapter.

CHAPTER 2

MULTIPLE TRANSPORTATION OBJECTIVES

Five major transportation objectives are identified in this research, which are user time equilibrium, system travel time, fuel consumption, vehicle emission and traffic noise. The objective of vehicle emissions can be further classified into three major emission components, namely carbon monoxide (CO), hydrocarbon (HC) and oxides of nitrogen (NO_x).

2.1 Description of Multiple Objectives

User Time Equilibrium

The user time equilibrium objective can be described by Wardrop's first assignment principle, which states that drivers behave in the route selections to minimize their own travel times. The traffic assignment based on the user time equilibrium objective results in a traffic loading where all used paths have equal travel times, which are less than or equal to all unused paths. The user time equilibrium represents a realistic and spontaneous behavior of drivers in making their route choice decisions.

System Travel Times

The system travel time objective represents Wardrop's second assignment principle which states that drivers behave to minimize the total network wide travel times in selecting their paths. The minimization of total system travel times results in a scenario where some drivers may select to take longer travel time routes in order for other drivers to reduce their travel times more significantly. The system time optimal is a more ideal objective and can only be realized through the system control and management, for example, through the applications of Route Guidance Systems.

Fuel Consumption

The fuel consumption objective is to save energy, which is not an unlimited resource on the earth. While the automobile industry strives to reduce the fuel consumption index through improvements in the internal design and structure of engines and vehicles, using traffic control and management methods to save energy is a new issue in transportation. The fuel consumption is of great importance to the environment and general public, because it is closely related to vehicle emissions.

Vehicle Emission

The reduction of vehicle emissions, which are pollutants emitted from automobile fuel, is an objective that helps clean the air pollution. The pollutants emitted from the vehicles are of concern to the public, as they are direct cause of numerous human ailments and health problems including pulmonary complaints, cancer, and vision problems. Among all of the automobile emitted pollutants, CO, HC and NO_x are the most significant species that pollute environments and influence public health.

Traffic Noise

The reduction of traffic noise is an objective that strives to minimize the effects of the unwanted and accumulated vehicle sounds. The problem of noise impact from traffic is unique in its spontaneity and lack of duration. Traffic noise, unlike other pollutants, leaves no residual evidence to serve as a continuing reminder of its unpleasantness. However, it is a major source of irritation and discomfort. Traffic noise factor is equally important as other environmental factors, but it will not be discussed further in this paper. Alternatively, it will be researched in a separate work.

2.2 Quantification of Each Individual Objective

In order to achieve the individual or the combination of the above objectives in a traffic assignment approach, each objective must be first quantitatively estimated. In addition, the methods for estimating the quantities must be made sensitive to the network flow dynamics in

order to evaluate the effects of different traffic scenarios and control and management strategies.

The user time equilibrium objective based traffic assignment methods have been studied by transportation researchers for decades. For static assignment methods, the user time equilibrium can be formulated into a mathematical program, whose solution by the Frank-Wolfe (Frank and Wolfe, 1965) algorithm has been proved to be consistent with the user time equilibrium conditions. For the dynamic traffic assignment, however, the formulation of a dynamic user time equilibrium objective becomes very difficult. As an alternative solution to this problem, the dynamic user equilibrium in the proposed approach is achieved using a heuristic algorithm, in the absence of an explicit mathematical objective function.

The system travel time optimal objective is defined as the total network travel times. It can be formulated as the summation of the travel times for all vehicles in the network for all time slices. In the proposed approach, after each dynamic traffic loading process is completed, the network wide system travel times can be calculated from the resulted link flows and times. The details of the dynamic loading process will be described in Section 3.2.

With respect to the calculation of the fuel consumption and vehicle emissions, numerous models have been developed in the past years. As to the fuel consumption, there primarily exist three types of models. One is called the average speed model (Tobin, 1979, Biggs and Akcelik, 1987 and Herman and Ardekani, 1985), which was developed mainly for transportation planning purposes and is not sensitive to the flow dynamics or the distribution of vehicles' modal events. This type of model, therefore cannot be used to evaluate the environmental implications of various traffic control and management strategies. The second type of the existing fuel consumption models is the power demand model (Post, et al., 1984) and its later derivatives the instantaneous model (Fist, 1989), which are based on the power requirements of engines and therefore cannot reflect the effects of traffic control and management strategies, and operational flow characteristics. The final type of the fuel consumption model is the drive mode elemental model (Penic and Upchurch, 1992 and Van

Aerde and Baker, 1994), which attempts to replicate the basic components of an individual vehicle's modal events, such as acceleration, deceleration, cruise and idle. This type of model can therefore reflect the effects of varying traffic flow dynamics and the traffic control and management strategies.

The model by Van Aerde and Baker (1994) was developed based on the field data collected from one test vehicle, 1992 Oldsmobile Torondo, which was equipped with the TravTek route guidance system (Krage, 1991). It therefore has no generality and cannot be applied to a network which contains the other vehicle fleet. The model by Penic and Upchurch, (1992) was developed based on a set of vehicles representing the current U.S. vehicle fleet and therefore it is appropriate for a relatively wide range of applications.

With respect to the vehicle emissions, the most popular and widely used model in the United States is the mobile source emission model MOBILE5 (USEPA, 1993). The MOBILE model can produce detailed vehicle emission information in terms of vehicle characteristics and operation conditions. It requests, however, only average speed as the sole indication of the traffic conditions. This model is, therefore, insensitive to the distribution of vehicle modal events and cannot be used to effectively evaluate the traffic control and management strategies that aims at reducing vehicle emissions.

New generation of modal emission models, which will be made sensitive to the vehicle's modal events and will cover the current national representative vehicle fleet, are under development by several agencies across the nation. The availability of a fully workable nation wide modal emission model, however, is estimated to be several years in the future. The emission models by Penic and Upchurch (1992), similar to its fuel consumption model, were developed from a set of vehicles that are representative of a wide range of performance capabilities of the current U.S. vehicle fleet. These models are therefore selected for the proposed approach in this paper and can be replaced by alternative models in a later time.

The fuel consumption and vehicle emission models by Penic and Upchurch (1992), compute the consumption, CO, HC and NO_x emissions based on the four modes of vehicles'

travel movement: acceleration, deceleration, cruise and idle. In the dynamic traffic assignment approach proposed in this paper, the acceleration and deceleration can be characterized by the vehicle's stop, which contains a deceleration motion from a cruise speed to a full stop and an acceleration event from the stop to the cruise speed. The number of stops, which are caused by either a red light of a traffic signal, or a traffic congestion, are therefore used to count the vehicle's modes of acceleration and deceleration. The idle times are characterized by the vehicle's delays, which can be calculated by the dynamic assignment model by accounting either the time waiting in front of the traffic signals or the time required for traversing an oversaturation queue. The cruise speed is estimated by calculating the average speed on each link excluding any delays.

CHAPTER 3

MULTIPLE OBJECTIVE ASSIGNMENT PHILOSOPHY

The first part of this chapter will propose and discuss the traffic assignment principles based on the new environmental objectives. The second part of this section will then describe the assignment/simulation procedures that are used in this report to search for the optimal solutions to the multiple transportation objectives.

3.1 Assignment Principles for Environmental Objectives

Most of the existing travel time based traffic assignment techniques were explored and developed based on one of Wardrop's two assignment principles. Wardrop's first assignment principle was referred to as User Equilibrium Principle and can be stated as follows: drivers travel through a network in a manner that results in a traffic loading where all used paths for each OD pair have identical travel times that are equal to or less than all unused paths. Wardrop's second assignment principle was known as System Optimal Principle and can be expressed as: drivers are routed through a network in a manner that results in a traffic loading where the resulting network wide travel time for all drivers is the minimum.

Similar to travel time based traffic assignment techniques, the development of the environmental criterion based traffic assignment methodologies also require the principles, which draw up the respective assignment objectives. Wardrop's two assignment principles can be simply extended to involve the environmental concerns, but the inclusion of the environmental variables into the objectives of traffic assignment methods results in extensive possibilities and considerations that cannot be entirely covered by Wardrop's two assignment logic. This research proposes four principles that can be used by the environmental assignment approaches. These principles are considered to be conceptual at this stage and need further improvements and modifications. The term of "environmental production" here represents the magnitude of either the fuel consumption, vehicle emission or traffic noise.

Principle 1 - User Equilibrium Environmental Assignment (UEE): This is a direct extension of Wardrop's first principle in regard to travel time based traffic assignment to

environmental assignment. This modified Wardrop's first principle can be stated as: drivers in a traffic network are routed through the network in a manner that results in a traffic loading where all used paths for each OD pair experience equal environmental production rates that are equal to or less than all unused paths. By this principle, drivers search for routes that will minimize their own fuel consumption, vehicle emissions or traffic noise, instead of traditional travel time measures.

Principle 2 - System Optimal Environmental Assignment (SOE): This principle is extended from the original Wardrop's second travel time based assignment principle. It is expressed as: drivers are routed through a traffic network in a manner that the network wide environmental productions are minimized. By this principle, some used paths for an OD pair may experience higher environmental production rates in order for some of other paths to have significant reduction in environmental productions.

Principle 3 - Community Equity Environmental Assignment (CEE): This principle is created from a potential reality that all communities/residents living along the links in a network may demand equal treatment with respect to the vehicle pollutant emissions and noise emissions. In other word, no community is willing to be polluted by traffic more than others. The assignment principle based on this consideration can be stated as: drivers in a traffic network are routed in a manner that results in identical environmental productions for all links in the network.

Principle 4 - Link Proportional Environmental Assignment (LPE): This principle is created from the possibility that the links in the network may have different acceptance limits relative to environmental productions. For example, a link along which few people reside may require different environmental constraints from a link with higher residential density. The assignment principle based on this consideration can be expressed as: drivers in a traffic network are routed in a manner that results in the environmental productions on each link proportional to the link's environmental acceptance limit. The link's environmental acceptance limit constrains the traffic in a similar way as link capacity constrains entry flows.

The Principle 1 is regarded as unrealistic for most of the real traffic network and control scenarios because of two principal reasons. In the first instance, the actual drivers in the network will not voluntarily consider the environmental factors in making their route choice decisions. In the second instance, the traffic engineers will also unlikely to manage vehicles in a manner that results in an environmental equilibrium. This principle is, however, not completely unrealistic for some extreme cases. For example, if the fuel price increases suddenly to such a high level that drivers become to consider the cost of fuel equal important as the travel time factors, then the individual drivers may possibly start to attempt to assign themselves to minimize their own fuel costs. This principle is considered not realistic today, but is proposed here for the completeness of all the potential principles for the environmental considerations

The Principle 2 is the most realistic condition, if the ITS related technologies are advanced sufficiently that drivers' route choice behavior can be intentionally and purposely influenced. The final objective of this principle is also consistent with the goals set by the CAAA of 1990, where the total amount of vehicle emissions are the major concerns. This research will, in the subsequent sections, focus on this principle in implementing the environmental based traffic assignments. Principle 3 and Principle 4 are two other potentials, which although are not unrealistic for a real traffic network but at least are extremely difficult to be realized in a traffic assignment model. It is felt, however, that it is worthwhile to present these two potential principles, which definitely need to be further researched in a later point.

3.2 Assignment/Simulation Procedures

The proposed approach in this paper uses the dynamic traffic assignment/simulation procedure, which was initially described by Yu and Van Aerde (1993). A subroutine for dealing with the environmental considerations, however, are incorporated in this research. The original dynamic assignment/simulation method was a mesoscopic approach which attempts to achieve either an actual time anticipatory user equilibrium or a system time optimal solution. The approach was designed as a discrete-time dynamic assignment approach, which discretized the entire analysis time period into a number of shorter time slices. The length of each time

slice could be either relatively short or long depending on the variability of the traffic conditions and the overall analysis purposes/objectives. The following description will demonstrate the primary components of the original dynamic assignment approach and the method for estimating environmental variables and the optimization logic for achieving multiple objectives in the new approach.

Use of Vehicle Packets

The dynamic assignment approach uses vehicle packets as the basic units in the traffic loading process. The traffic demands within each time slice for an OD pair are organized into a number of packets. The size of a traffic packet is determined depending on how many incremental steps one desires to use in assigning the entire traffic demand that departs for a given OD during a given time slice. For example, when the departure traffic demand rate is 1,000 veh/hr during a given time slice, and the time slice length is 10 minutes, the packet size will be 16.67 vehicles if 10 incremental steps are required ($1,000 \cdot (10/60) / 10$). The fact that the packet size is a function of the user specified incremental size indicates that this packet size will automatically be different for different analysis time slice duration. For example, if the traffic demand for another 10 minute time slice was 1,200 veh/hr, the packet size for that time slice would become 20 vehicles ($1,200 \cdot (10/60) / 10$). It can be noted from the above example that a packet size is neither constant, nor required to be an integer.

The vehicles within each packet are held together as a unit during its entire trip throughout the network. Each vehicle packet is assigned to a minimum path that corresponds to the given packet's departure time slice and its sequence number. When there exists more than one minimum paths within a given time slice, the vehicle packet will be assigned deterministically to one of the candidate paths in such proportions as to match best the minimum path weights that have been computed. If a packet transitions from one time slice into the next, it will automatically select the path for the remaining portion of its trip based on the multiple paths for this new time slice. The use of multiple paths during each time slice, coupled with the use of different paths in consecutive

time slices, ensures that a vehicle packet can always follow one of the up-to-date multiple paths along its trip to its destination.

The use of vehicle packets can ensure the better treatment of oversaturation queues in the network, as well as explicitly distinguish the vehicle's modal events, namely acceleration, deceleration, cruise and idle, which are essential for calculating the environmental productions. The flexibility of the packet size also provides an opportunity for the modelers to trade-off between the accuracy of the results and the model execution time.

Link Flow and Travel Times

The proposed approach describes the link flows with three flow variables. The first is the entry flow to the link, which is the summation of the flows from all the contributed upstream links. The second is the flow at the tail of the oversaturation queue in front of the downstream node, which is virtually the entry flow after experiencing a time lag, which equals the link travel time. The third is the flow at the head of the oversaturation queue in front of the downstream node, which is derived from the flow at the tail of the same queue after experiencing a time lag, which equals the queue delay. The representation of link flows in this way makes it possible to describe the vehicle propagation along a link accurately and trace an oversaturation queue microscopically.

In the dynamic traffic loading process, the link travel times are functions of the link flows, and the link flows are functions of the link travel times experienced along the upstream links. Assigned link flows and link travel times, which are computed based on the assigned link flows, are mutually dependent. In order to converge these link flow and link travel time estimates to a consistent set of values, an iterative process is utilized in the loading of traffic.

Specifically, the traffic is initially loaded by computing downstream arrival lags based on free flow travel times. Subsequently, new link travel times are computed based on these assigned flows. The traffic is then reloaded based on the new estimates of the link travel time lag impacts, and a new set of link travel times can be computed based on the new link traffic loading.

Description of Oversaturation Queues

By the end of each iteration of the traffic loading process, the flows at the tail of each oversaturation queue for a given time slice are compared with the respective link exit capacity for the same time slice. If this flow is larger than the exit capacity, a new oversaturation queue is calculated based on the difference between the flow and the capacity. The flows at the front of the exit queue will be automatically constrained to a value, which is approximately equal to the link's exit capacity during the traffic loading.

When a vehicle packet is assigned to its minimum path and queues are met on any earlier links, the waiting times/queue delays in these queues have to be computed, such that one can determine precisely during which time slice the assigned packet should be added to each subsequent downstream link flow. The waiting time at a queue is a function of the queue size and the exit link capacities in the current, as well as any relevant subsequent time slices. Different magnitudes of the exit capacities will therefore result in different dissipating times for queues of the same size. Consider, for example, that a vehicle packet that reaches the tail of a queue during a time slice can pass completely through the entire queue within the same time slice, then the waiting time will be computed as [queue length during that time slice]/[link capacity for that time slice]. If, however, a vehicle packet cannot complete its movement to the front of the queue within the initial time slice during which the packet joins the queue, the waiting time for the remaining time that the vehicle must spend in queue is calculated recursively based on the capacities of the subsequent time slices.

Calculation of the Environmental Productions

The vehicle's modal events must be identified in the traffic loading in order to estimate the impact of the changes of traffic control and management strategies on the fuel consumption and vehicle emissions. The distribution of the vehicle's modal events, which include the acceleration, deceleration, cruise and idle, is identified in the proposed approach in a dynamic basis.

A vehicle's full stop can be described by a deceleration from a cruise speed to the 0 speed and a acceleration from the 0 speed to a full cruise speed. Any stops of the vehicle

packets, due to either oversaturation or traffic signals, will be separated into various acceleration and deceleration events. The number of stops caused by a traffic signal is estimated from the percentage of the red time that is assigned to the link approach of interest for a particular time slice. The number of stops caused by an oversaturation/congestion will be counted depending on if a particular vehicle packet can meet any oversaturation queue during its trip at a given time spot.

The cruise speed is estimated based on the link length and the corresponding link travel times excluding any delays. Any small changes of the speed, which may also lead to the occurrences of acceleration and deceleration events, are not considered at the current stage of the proposed approach. The effects of these small acceleration and deceleration events, however, can be taken into account by estimating the level of speed variability and therefore the number of occurrences of certain acceleration or deceleration events.

The vehicle delays are used as the idle time relative to the vehicle's modal events. Any delays caused by a traffic signal are estimated from the phase timing split of the same signal and the total approaching flow rates to the intersection of concern. The delays of a vehicle incurred by the traffic congestion will be estimated as the time required for traversing the corresponding oversaturation queue.

With the identification of these vehicle's modal events, the fuel consumption and vehicle emission quantities can therefore be estimated. It should be noted that any change of the network wide traffic control and management strategies, such as traffic signal plans, ramp metering controls, traffic incident management and High Occupancy Vehicle (HOV) lane operation, will directly affect the distribution of vehicle's modal events, and therefore the quantitative estimates of fuel consumption and vehicle emissions.

Traffic Loading Process

The final traffic loading process of the proposed approach, which does not include minimum path finding and traffic weight/split calculation, can be summarized in the following table:

TABLE 1:
Steps in the Traffic Loading Process of the Proposed Approach

Step 1. Fix the link travel times, delays, queue sizes, fuel consumption and vehicle emissions for the whole network. For the first iteration, link travel times are made to be equal to free flow link travel times, and other quantities are made to be zero. Increase the iteration counter by 1.

Step 2. Choose a traffic demand for one OD pair and a given time slice. Organize the associated traffic flows into a list of vehicle packets, based on a specified total number of vehicle packets to be used. Organize the departure time of each packet based on the time slice length and the total number of packets.

Step 3. Select one vehicle packet from this list and trace the minimum path that the packet is required to follow from its origin to its destination. The tracing of the minimum path is based on the weight of each path and the packet's sequence number. The arrival lag times to each link are used to determine which minimum path the packet should take at a diversion node when multiple minimum paths and multiple time slices are present.

Step 4. Add the vehicle packet to the corresponding link flow counter along its minimum path to its destination, and update the link flows in the corresponding time slices. Estimate any delays and the number of stops caused by the traffic signals and oversaturation queues and add the delays on the travel cost along the path of interest. Estimate the approximate cruise travel speed on each link for a given time slice.

Step 5. If the packet is not the last one for the given OD demand within the given time slice, return to Step 3, otherwise proceed to the next step.

Step 6. If the OD demand is not the last one from which departures are to be assigned during a given time slice, return to Step 2, otherwise proceed to the next step.

Step 7. Compute new link travel times for all links and time slices. Calculate the oversaturation queues for the links where any oversaturation occurs.

Step 8. If the link travel times and delays obtained from this iteration have not reached close enough to those that were calculated from last iteration and the specified maximum number of iterations has not been exceeded, returns to Step 1. Otherwise proceed to the next step.

Step 9. Compute the network wide system travel times, total fuel consumption and vehicle emissions considering all links and all time slices and stop.

Optimization Logic for Multiple Objectives

The objective of the proposed dynamic traffic assignment approach is to achieve either a dynamic user time equilibrium, or the minimization of the system travel time, the fuel consumption, the vehicle emission or a multiple objective. The proposed approach uses a successive average method to achieve the actual time anticipatory user equilibrium and a tedious search method to find the other optimal solutions.

In the successive average method for the user time anticipatory equilibrium, a single set of paths is built first for all the time slices. When a new path for a time slice is built, it is assigned a lambda value, which is defined as the percentage of the traffic that is assigned to the new path, of $1/n$, where n is the total number of paths that have been found for that time slice to date. Some of traffic assigned to the previous paths will be reassigned to the new found path based on the selected lambda value. When multiple paths for each OD pair are found in this way, the network flows are expected to approach an user time anticipatory equilibrium.

In the tedious search method, the lambda value for each new path, which results in the minimum objective function estimate, is selected. As the total system travel time, fuel consumption and vehicle emission can be calculated at the end of each traffic loading process, it is possible to compare these values by altering the lambda value at a given step size. Similar to the successive average method in the user time equilibrium, a set of single paths is built for all time slices initially. These initial paths are assigned a lambda value of 1.0 and therefore their weights are also set to 1.0. After a new path is built, all the potential lambda values between 0.0 and 1.0 starting from the value of 0.0 with a pre-specified step size, for example 0.05, are tried. The resulting system travel times, fuel consumption or vehicle emission estimates for different lambda values are compared and the one that results in the minimum value is selected for this new path. All the following minimum paths will experience the same procedure for finding their respective lambda values.

General Algorithm

The general algorithm for the proposed approach involves three distinguished modules. Specifically, MODULE 1 will identify the minimum paths for all OD pairs relative to the network loading that were performed to date. MODULE 2 will calculate weights for the routes, which were identified in MODULE 1, in order to either achieve dynamic user equilibrium or minimize the system travel times, fuel consumption, vehicle emissions or a combined objective. MODULE 3 is a convergent algorithm that computes consistent sets of link flows and link times with an iterative approach. The whole algorithm of the proposed approach is described in the following table:

TABLE 2:

General Algorithm of the Proposed Approach

<p>Step 1. Build the first set of minimum paths for all time slices based on link travel times for an empty or unloaded network. This process finds the minimum paths from all origins to all destinations during all time slices. Set the weights equal to 1 for all of these initial minimum paths. (MODULE 1 and MODULE 2)</p> <p>Step 2. Load all the OD demands onto the network dynamically based on the minimum paths that have been built in Step 1. (MODULE 3)</p> <p>Step 3. Build a single new path for a time slice based on the estimates of link travel times from Step 2 (Iteration 1) or Step 5 (Iteration 2). (MODULE 1)</p> <p>Step 4. Calculate the lambda value to be placed on the new path considering either dynamic user time equilibrium, system travel times, fuel consumption, vehicle emissions or a multiple objective. (MODULE 2)</p> <p>Step 5. Re-load, in a fashion similar to Step 2, all the OD demands onto the network dynamically, based on the paths that have been built to date in Step 3 and using the lambda values found in Step 4. (MODULE 3)</p> <p>Step 6. If more lambda values should be tried, return to Step 4. Otherwise, proceed to the next step.</p> <p>Step 7. Fix lambda value for the new minimum path for the given time slice.</p> <p>Step 8. If all the specified number of minimum paths for all the time slices have not yet been built, return to Step 3. Otherwise, stop.</p>
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CHAPTER 4

NUMERICAL EXAMPLES

This chapter will use a hypothetical traffic network to examine the proposed approach for the selected traffic and control scenarios. Section 4.1 will first describe the geometric layout of the hypothetical network. Section 4.2 will then examine the implementation of the proposed approach for each particular objective with an assumption that a traffic incident occurs in the network. Section 4.3 will finally examine a network scenario where a traffic signal is in place and the red time duration of the signal is the major cause of the vehicle stops.

4.1 Description of the Example Network

The geometric layout of the hypothetical network is shown in Figure 1. This network contains 5 nodes and 5 links. Node 1-3 are assumed to be the sources where the trips generate and sink. Node 4 is a signal controlled intersection, while Node 5 is a non-signal controlled intermediate node. All the links in the network are given the identical characteristics and capacities, in which the link length is assigned a value of 2 kilometers, the free flow speed is given 60 kilometers per hour and the capacity is made 2000 vehicles per hour with a single lane. The analysis time slice length will be fixed to 2 minutes for all scenarios.

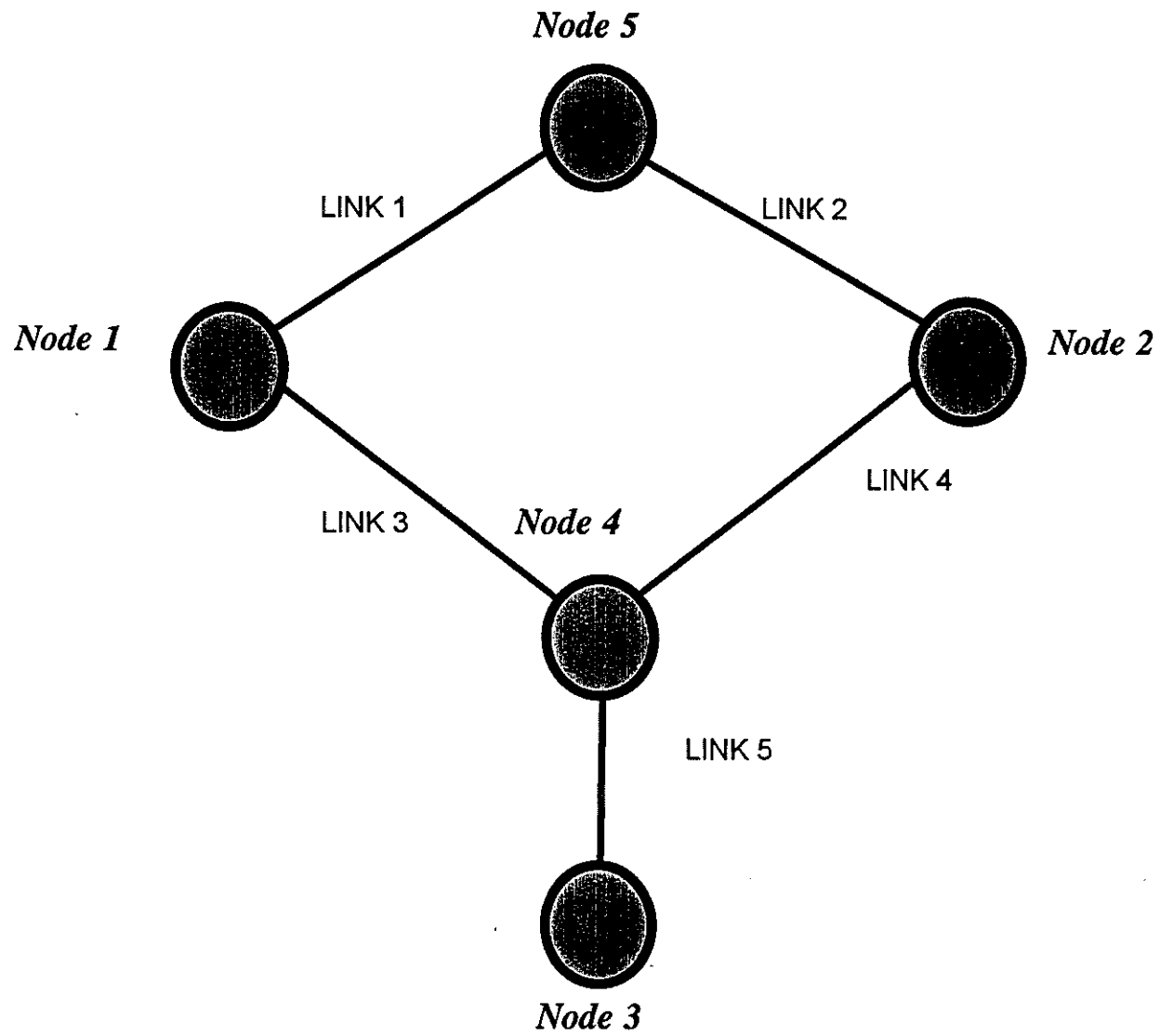


Figure 1: Geometrical Layout of the Hypothetical Traffic Network

4.2 Incident Scenario

The scenario in this section assumes that a travel demand of 2000 vehicles per hour from Node 1 to Node 2 lasts exactly one hour. No trips are assumed to travel from Node 3 and therefore the traffic signal at Node 4 is made to assign 100% of its cycle time to Link 3 for the trips traveling from Node 1 to Node 2. A traffic incident occurs at the downstream end of Link 3 during 20-40 minute period which blocks 80% of the link capacity. The majority delays and the stops in the network will be caused by the traffic incident. The summary of the implementation results is presented in Table 3.

The proposed assignment approach is implemented based on 7 different objectives, namely user time equilibrium, system travel time, total fuel consumption, total vehicle emission, CO emission, HC emission and NOx emission. The system travel time, fuel consumption and vehicle emission are then estimated from the outputs of each run of the dynamic assignment.

Figure 2 illustrates the total system travel time and the total fuel consumption resulted from each implementation of the proposed approach. It is shown that the user time equilibrium based assignment resulted in the highest total travel time, while the system time based assignment resulted in the lowest total travel time. In addition, both user time equilibrium based and system time based assignments resulted in high fuel consumption, which implicates that none of the travel time based assignments can be used as approximation to the fuel consumption based assignment. It is also shown, from the same graph, that both consumption based and emission based assignments resulted in similar total travel time and fuel consumption, although the consumption based assignment resulted in the lowest fuel consumption.

Table 3:

Summary of the Implementation Results of the Designed Traffic Scenario

Traffic Incident Scenario						
Objectives	Total Times (veh-mins)	Consumption (gallons)	Emissions (grams)	CO (grams)	HC (grams)	NOx (grams)
User Equilibrium	13377	197	5903	4992	380	531
System Time	12678	198	5678	4782	377	519
Consumption	12842	196	5554	4668	373	512
Emissions	12855	196	5555	4669	373	512
CO	12842	196	5554	4668	373	512
HC	12842	196	5554	4668	373	512
NOx	12855	196	5555	4669	373	512
Traffic Signal Scenario						
Objectives	Total Times (veh-mins)	Consumption (gallons)	Emissions (grams)	CO (grams)	HC (grams)	NOx (grams)
User Equilibrium	21759	318	11542	9953	639	951
System Time	20258	321	11117	9550	641	927
Consumption	20326	307	9924	8474	602	848
Emissions	20554	310	9764	8316	606	842
CO	20554	310	9764	8316	606	842
HC	20326	307	9924	8474	602	848
NOx	20642	311	9743	8297	606	840
Comparisons of Two Signal Scenarios						
Objectives	Total Times (veh-mins)	Consumption (gallons)	Emissions (grams)	CO (grams)	HC (grams)	NOx (grams)
User (Signal-1)	21759	318	11542	9953	639	951
User (Signal-2)	20207	308	10394	8905	609	880
Difference	1552	10	1148	1047	30	71
System (S1)	20258	321	11117	9550	641	927
System (S2)	20246	311	10318	8830	612	873
Difference	12	11	799	720	28	53

Total Travel Times and Fuel Consumption

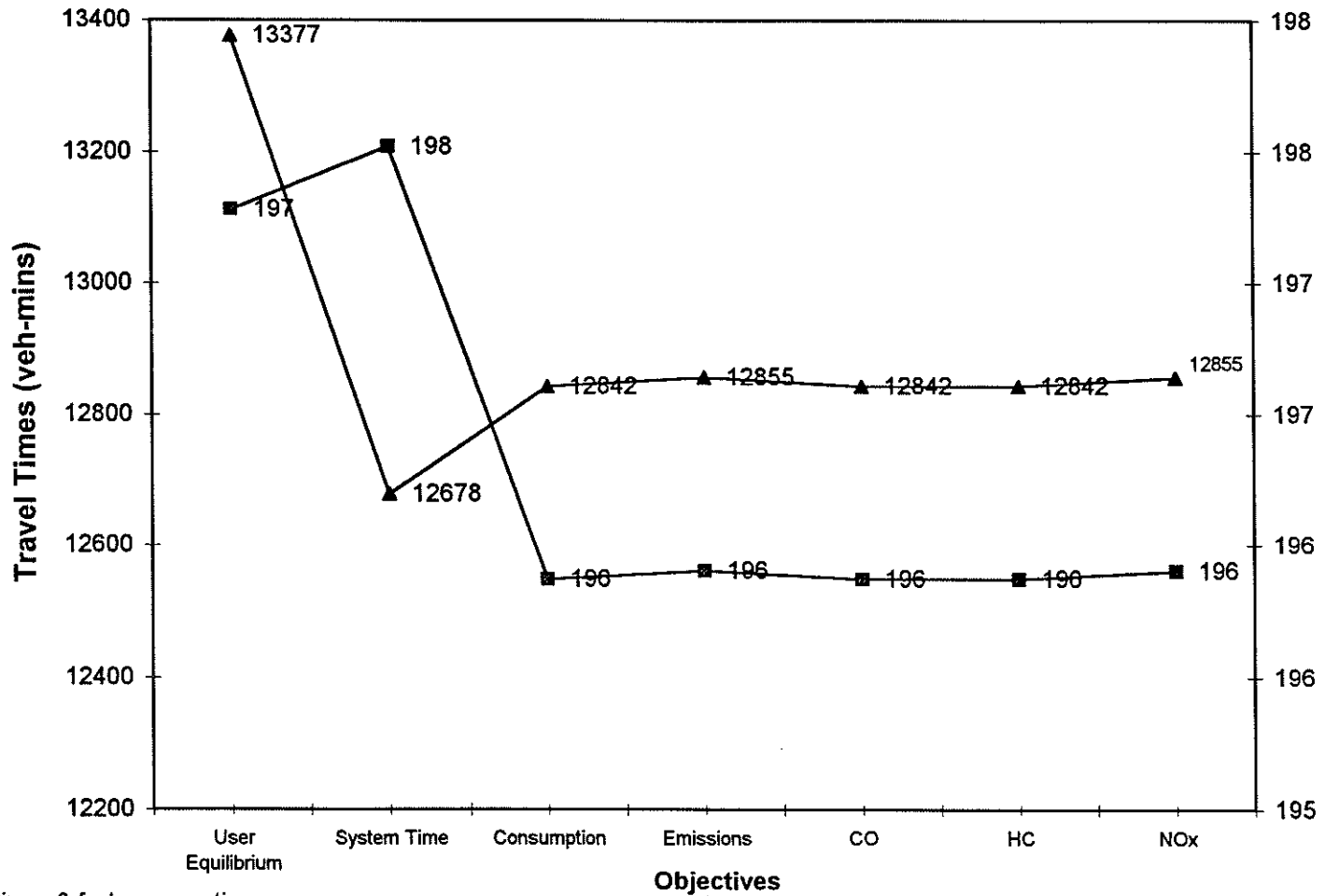


Figure 2: Total times & fuel consumption of the traffic assignments based on different objectives for the traffic incidents scenario



Figure 3 illustrates the total fuel emission values, which were obtained from each implementation of the proposed approach. The user time equilibrium objective resulted in the highest values for all kinds of emissions and the system time objective resulted in higher emissions than both consumption and emission objectives, which again implicates that the travel time based traffic assignments are not appropriate for use in a situation where vehicle emissions are major concerns. The Figure 3 also shows that CO emission occupies the largest portion among all the vehicle emissions, and that the total emission based assignment and the CO emission based assignment resulted in about the same trends in the curves. The magnitudes of the HC and NO_x emissions were relatively small, which however does not mean that they are less important pollutant species than the CO emissions. Actually the significance of each kind of emission is dependent not only on the absolute amount, but also on the severity which it affects on the public health. For example, HC and NO_x, which are although small amounts comparing with CO, combined with sunlight and other factors, will form the ozone (O₃), which is a major threat to our human's life.

4.3 Signal Scenario

Traffic demands are assumed to come from both Node 1 and Node 3 heading for Node 2 in this scenario. The traffic signal at Node 4 will give 50% of its cycle time, which is set to 120 seconds, to Link 3 and 50% to Link 5. The loss times of the signal for both phases are fixed to 5 seconds. Travel demands from Node 1 and Node 3 are respectively set to 2500 and 500 vehicles per hour for an entire hour period. The delays and stops in this scenario are primarily caused by the red time of the traffic signal. (See Table 3: Traffic Signal Scenario).

Figure 4 illustrates the total travel time and fuel consumption for the network for which the assignment is carried out based on different objectives. Similar to Figure 2, the user time equilibrium based assignment resulted in the highest system travel time, while the system time based assignment resulted in the highest fuel consumption. In addition, the fuel consumption based and the HC emission based assignment resulted in

the identical traffic loading, which incurred equal fuel consumption amount and the total system travel time, which are lower than the other emission objective based assignments.

Figure 5 illustrates the amount of emissions of each emission species resulted from different assignment implementations. Similar to the observations from Figure 3, CO emissions take most of the portions of the total emissions. Also, the emissions resulted from the different environmental objective assignments are very close, which implicates that assignment based on one kind of environmental objective may be used as the approximation to any of the other emission based assignments.

All the above graphs represented the comparisons of total travel time, fuel consumption and emission, which were obtained from the implementation of the proposed approach based on different assignment objectives. In reality since most of the real traffic networks will be still assigned of traffic according to the traditional user time equilibrium principle, it is necessary to evaluate the environmental implications of alternative traffic control strategies based on the same user time equilibrium objective. In the particular scenario in this section, an alternative traffic signal timings, which assigns 70% of cycle time to Link 3 and 30% to Link 5, was also applied to the network. The implementation of this new signal control scenario resulted a reduction of 1552 vehicle-minutes in total travel time, 10 gallons in fuel consumption, 1148 grams in total vehicle emission, 1047 grams in CO emission, 30 grams in HC emission and 71 grams in NOx emission (See Table 3: Comparison of Two Traffic Signal Scenarios). The proposed approach can, therefore, be used to evaluate the environmental implications of various traffic control and management strategies based on either the same or different objectives.

Fuel Emissions Based on Different Objectives

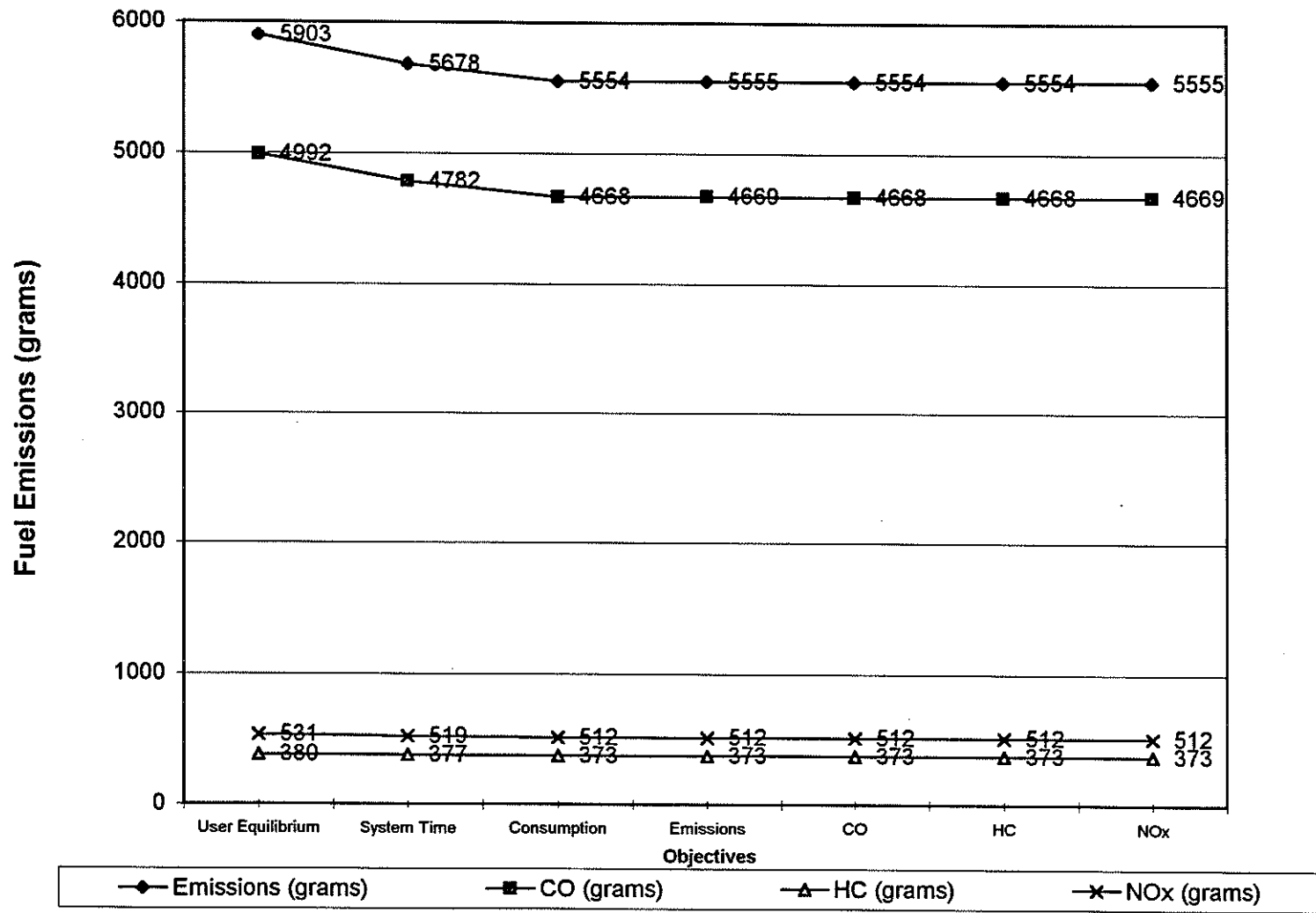


Figure 3: Vehicle emissions of the traffic assignments based on different objectives for the traffic incident scenario

Total Travel Times and Fuel Consumption

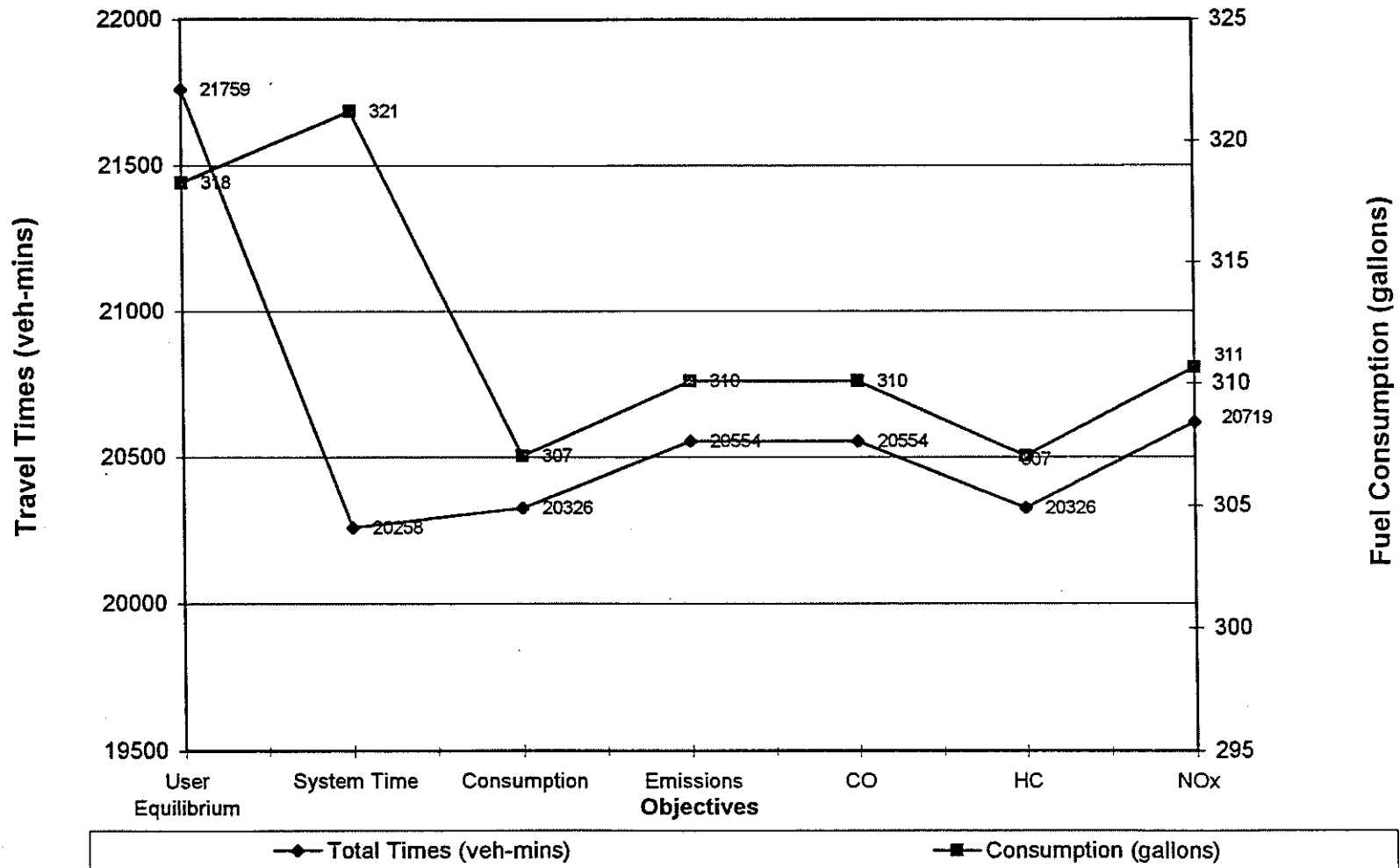


Figure 4: Total times and fuel consumption of the traffic assignments based on different objectives for the traffic signal scenario.

Fuel Emissions Based on Different Objectives

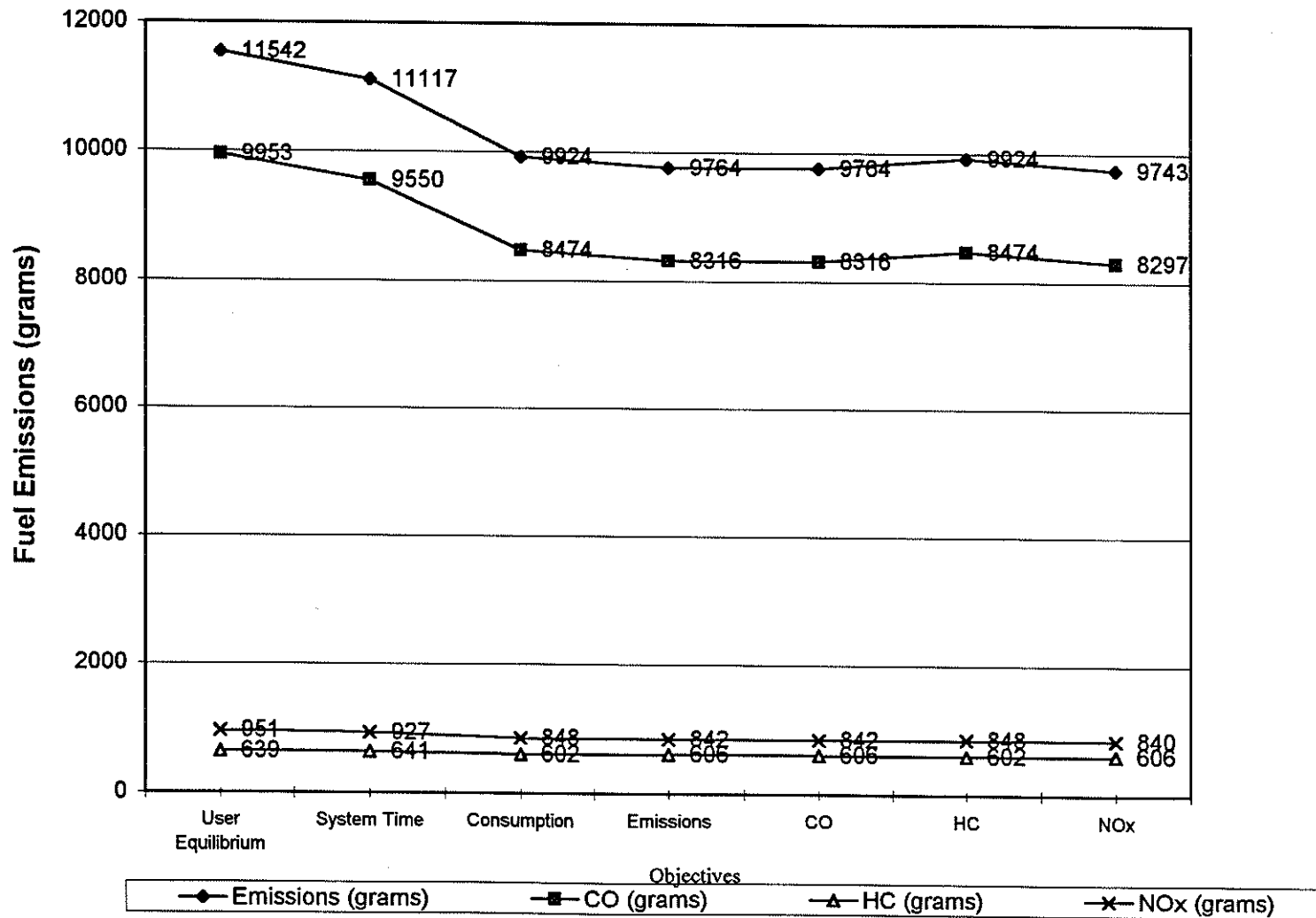


Figure 5: Vehicle emissions of the traffic assignments based on different objectives for the traffic signal scenario

CHAPTER 5

CONCLUSIONS

This research presented an approach, which can perform the dynamic traffic assignment logic based on multiple transportation objectives. The proposed approach can search for the optimal solution of each particular objective and estimate the respective network assignment results. Each particular objective based non-user equilibrium traffic assignment and loading can be eventually realized with the advances and applications of telecommunication technologies, route guidance systems and electronic road pricing. The new approach can be used to evaluate the travel time and environmental implications of alternative traffic control and management strategies.

The example network and traffic scenarios indicated that the travel time based assignments, either by user time equilibrium or system time optimal, are not appropriate for use in a situation where the environmental variables are the major consideration, especially when the queues and delays are present. While all the environmental variables were estimated from the distribution of vehicle's modal events, each particular estimation was shown to be more or less sensitive to each individual modal event. In general, however, it can be concluded that one environmental variable based assignment can be used as the approximate estimation of the other environmental variable based assignments.

The estimation of quantities of the fuel consumption and vehicle emissions were made from a set of selected formulas. It is felt that these formulas should be replaced with more sophisticated models, which can better reflect the sensitivity of each environmental factor to the distribution of the vehicles' modal events.

The recommended research following this work includes the incorporation of traffic noise variable into the objective function of the current model. In addition, it is useful to investigate a generalized objective function, which may be comprised of a weighted combination of all the existing objectives. The selection of a particular weight

for each objective and its significance to the final assignment results should also be examined.

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