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# A CONCEPTUAL EXAMINATION OF THE IMPACT OF TRAFFIC CONTROL STRATEGIES ON VEHICLE EMISSIONS AND FUEL CONSUMPTION

by

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**FINAL REPORT**

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16. Abstract

The federal government has charged the Environmental Protection Agency (EPA) with the responsibility of controlling and/or reducing the adverse levels of vehicle emissions, which result in unacceptable amounts of environmental pollution nationwide. In order to achieve this goal, the EPA, in turn, has mandated the installation of control technology in newer vehicles and more environmentally friendly new fuels. Theoretically, though, additional success could be achieved through the use of more emission sensitive traffic control strategies. The feasibility of this assumption can be tested by studying the real impacts of today's advanced technology applications in transportation management on environmental factors. These impacts, in fact, are the basis for the design and implementation of a new generation of traffic management strategies.

However, the fact is that traditional traffic control strategies and/or traffic modeling programs, designed to comply with EPA requirements, have focused on travel time as their basis for reduction objectives. It should be understood, however, that these travel time minimization strategies, in general, do not simultaneously minimize fuel emissions or fuel consumption and hence, may not meet the environmental goals sought by EPA.

Specifically, different traffic management operational strategies can have different effects on a vehicle's speed profile, which includes acceleration, deceleration, cruise and idle events. Further, it is these speed changes that affect the levels of the vehicle's tailpipe emissions, which are made up of the potentially harmful pollutants of Hydrocarbons (HC), Carbon Monoxide (CO), and Oxides of Nitrogen ($NO_x$), and fuel consumption. These emissions therefore, are sensitive to the traffic control strategies, such as signal timing settings, ramp metering, incident management, HOV lanes and toll collection utilized in real networks.

The objective of this research is to investigate some of the specific relationships between traffic signal settings and the resultant effects on vehicle fuel consumption, emissions levels and travel times as a means of identifying a basis for deriving optimal, environmentally sensitive traffic control strategies.

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# EXECUTIVE SUMMARY

Air quality and fuel consumption have long been concerns for environmental government agencies led by the Environmental Protection Agency (EPA), and are thus, increasingly becoming more of a factor in nationwide planning strategies. The Clean Air Act Amendment (CAAA) of 1990, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, and its successor, the Transportation Equity Act for the 21st Century (TEA-21), for instance, have all placed more emphasis on the responsibilities of all Metropolitan Planning Organizations (MPOs) to account for and achieve their overall environmental goals. To be certain, the effectiveness or success of congestion mitigation and traffic management strategies will be dependent on their demonstrated ability to at least ensure no further degradation of air quality levels in specific urban air quality basins as suggested by An et al. (1996).

As is currently the practice, transportation engineers and planners, alike, consider environmental mitigation objectives only as incidental aspects (or effects) of the travel time-based objectives that are typically sought. In other words, the generally accepted concept in designing and implementing traffic models and traffic control strategies is that minimizing trip times will subsequently result in reducing potentially harmful vehicle emissions and fuel consumption rates called for in federal environmental programs. Some recent research findings, however, point to the fact that travel time variables are affected differently from air quality and fuel consumption variables by the various traffic control methods and strategies realized by these models (Yu, 1997). Because emissions and travel times display different sensitivities to speed, it is important to develop different traffic control and/or management strategies that would take this relationship into account and thus be more effective in minimizing emissions.

Operational traffic control strategies employing the use of traffic signals, ramp metering, traffic incident management and changeable message sign controls determine the number of vehicle stops, which in turn, characterize the average modal event experienced in a given network. The research by Yu and Stewart (1995) has shown that the magnitudes of vehicle emissions are heavily affected by the distribution of these modal events; while on the other hand; the travel time factors are affected by vehicle average speed.

With this understanding, the objective of this research is to demonstrate, by using the DYNAMIC traffic assignment/simulation model, the conceptual relationship between traffic control strategies and potentially harmful vehicle emissions. The dynamic traffic assignment and simulation method, as opposed to the static method of modeling, is used in order to be more representative of the time series of vehicles' modal events and, thus, more accurately estimate the impacts of alternative traffic control scenarios on various travel time and environmental factors including pollutants and fuel consumption.

Subsequently, this paper tries to demonstrate that emission or fuel consumption reduction is not necessarily achieved through the same traffic control techniques that are usually employed for reducing travel times.

The selected dynamic traffic assignment approach can quantitatively estimate the distribution of vehicles' modal events which consist of periods of acceleration, deceleration, cruise and idle, which can then be used for estimating the amounts of fuel consumption and emissions. These quantities can then be used for analytical comparison and, thus, as a basis for deriving optimum mitigation strategies.

Transportation emission estimation models generally combine the elements of traffic assignment values and emission rates based on variables such as vehicle type, speed profiles and climatic conditions. Therefore, emission models are designed to estimate emissions as a function of network route assignments and emission factors.

These two elements are sometimes integrated into a single model like INTEGRATION or DYNAMIC. Alternatively, dedicated emissions models using inputted assignment values are also used to estimate emission quantities.

Currently, there are two static emission factor models used in modeling and estimation of the environmental pollutants mentioned previously. These models are MOBILE5a and EMFAC, and both use as their basis of evaluation, vehicle average speed as the sole descriptor of the vehicle's modal events.

The DYNAMIC program was used in this research to analyze the environmental and travel time impacts of traffic control alternatives. The following is an overview of the operational elements of the DYNAMIC model.

DYNAMIC model is a FORTRAN program that can dynamically assign a given traffic demand to a congested traffic network based on either of two travel time objectives, user and system equilibrium, or various environmental objectives. The program, developed by Yu (1996), uses vehicle packets as the basic units in the traffic loading process. The traffic demands associated with each time slice for an Origin/Destination (OD) pair is organized into a number of packets. The size of a vehicle packet is dependent on the number of incremental steps assigned to the traffic demand for a given OD pair during a given time slice. The effect of various traffic signal plans is achieved in this examination, by placing traffic signals throughout a network within DYNAMIC and adjusting the cycle lengths through a range of 30 to 120 seconds.

Traffic signal control timings are adopted in this examination as the basis for modeling a general traffic control strategy, primarily because of the effectiveness of traffic control signal timings to define vehicular speeds throughout a given network. It is important to note that tailpipe emissions and fuel consumption have a direct relation to a vehicle's modal activity as defined by starts, stops, acceleration and deceleration and overall average speed. Adjusting traffic control signals, therefore, is a positive means of controlling traffic behavior within a network, which has the potential to affect environmental production levels. In other words, traffic signal timing is used as the basis for general traffic control strategies because of its inherent ability to define the overall modal activity of vehicle movement throughout a signalized roadway network.

Three basic scenarios are used to examine the behavior of emissions, fuel consumption and travel time variables against different operational objectives and traffic signal settings. The results of the first scenario support the traffic assignment principles discussed previously, showing that the levels of vehicle emissions, fuel consumption and travel times change directly and independently for different operational objectives specified in the dynamic assignment. It should be noted that the operational objectives such as travel time (total and individual), fuel consumption, and fuel emissions (environmental pollutants) were each factored in as an independent operational objective of the traffic network. The resulting emission levels, therefore, are based on the simulated assignment for each objective.

The preliminary results of the second scenario show general decreases in travel times, fuel consumption and emission levels as the cycle length and effective green time are increased. It is significant that the total travel time shows a greater improvement of about 62% compared to just about 8% reduction in time for user equilibrium. Notably, the rate of decrease is about the same for consumption and emissions as it is for user travel time. Consumption and emission levels decreased by about 5% over the range of signal lengths. This implies that total travel time benefits most (in this network) with longer cycle lengths.

Notably, total emissions level actually decreases at the 60-second cycle length. This trend is noted for the levels of CO and $NO_x$ emissions specifically, while HC levels tend to flatten at the same cycle length. This would suggest that there maybe an optimum cycle length that would simultaneously minimize travel time and emissions.

The third scenario examines the effect on fuel consumption, tailpipe emissions and travel times, by approximating the simulation of a more controlled network. Adding a second traffic signal to the network creates this effect. Again, all the variables show decreases as the signal length increases. As expected, with more restrictions to traffic flow, as a second signal placed in the network will create, vehicle performance is compromised resulting in greater fuel consumption and degradation of emission levels.

Based on the findings of this research, it thus can be concluded that first, the analysis of emissions modeling requires an explicit formula that takes into account its individual behavior compared to travel time based modeling. As previously outlined, models and formulas traditionally used in traffic assignment routines are not explicit enough to account for the various components of a vehicle's driving profile.

Second, it can be concluded that traffic control strategies, at least through signal timings, is an effective approach to mitigating tailpipe emissions even though it may result in losing some travel time benefits.

Another conclusion is that the concept of using traffic signal controls to obtain certain environmental results is feasible. It is recommended, therefore, that further efforts be made to examine these basic relationships between tailpipe emissions and traffic signal manipulation. It is further recommended that the scenarios be structured within more complex, real-world networks that would offer the basis of a framework for developing optimum signal settings for improving network travel times while mitigating emissions productions.

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# CHAPTER 1

## INTRODUCTION

Air quality and fuel consumption have long been concerns for environmental government agencies led by the Environmental Protection Agency (EPA), and are thus, increasingly becoming more of a factor in nationwide planning strategies. The Clean Air Act Amendment (CAAA) of 1990, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, and its successor, the Transportation Equity Act for the 21st Century (TEA-21), for instance, have all placed more emphasis on the responsibilities of all Metropolitan Planning Organizations (MPOs) to account for and achieve their overall environmental goals. To be certain, the effectiveness or success of congestion mitigation and traffic management strategies will be dependent on their demonstrated ability to at least ensure no further degradation of air quality levels in specific urban air quality basins as suggested by An et al. (1996).

In order to effectively manage air quality and other travel-related environmental programs, it is necessary to be able to correctly define the explicit variables that affect the impact of vehicle emissions and fuel consumption. These variables must then be modeled or simulated to derive a theoretical evaluation of the specific proportions of pollutants generated. The understanding here is that the primary air quality objective in traffic operations and management can be defined as mitigating vehicle emissions of Carbon Monoxide (CO), Hydrocarbons (HC), and Oxides of Nitrogen ($NO_x$).

The transportation community has long established that driving conditions substantially influence vehicle fuel consumption and tail pipe emissions. This is to say that a vehicle's modal activity, which involves periods of acceleration, deceleration, cruise, and idle, determine the vehicle's environmental production. It is also widely accepted that traffic controls in use today, such as traffic signals, ramp metering, and changeable message signs are designed, primarily, to control vehicle flow in order to minimize congestion and, thus, reduce total and individual travel times.

It should be noted, therefore, that finding optimal traffic control strategies that have the potential to minimize vehicle emissions are needed and the effectiveness of these strategies are dependent on the sensitivity of the methods used. More specifically, the computer programs and mathematical models traditionally used in modeling transportation scenarios as a means of evaluating various traffic options have to be specific to environmental concerns as opposed to just seeking optimum travel times objectives.

As is currently the practice, transportation engineers and planners alike consider environmental mitigation objectives only as incidental aspects (or effects) of the travel time-based objectives that are typically sought. In other words, the generally accepted concept in designing and implementing traffic models and traffic control strategies is that minimizing trip times will subsequently result in reducing potentially harmful vehicle emissions and fuel consumption rates called for in federal environmental programs. Some recent research findings, however, point to the fact that travel time variables are affected differently from air quality and fuel consumption variables by the various traffic control methods and strategies realized by these models (Yu, 1997). This observation is explained in the following section.

## **Description of Different Objective-Based Assignments**

As noted earlier, the lack of efficient methods for estimating vehicle fuel emissions and fuel consumption can be attributed to the traditional perception within the transportation community that believes the minimization of travel times will concurrently result in associated reductions in the undesirable environmental byproducts of vehicle travel. In some cases, this perception is true, such as in a typical freeway operation scenario. On the other hand, there are other traffic scenarios, such as traffic signal controlled networks, where the two objectives are not achieved simultaneously. The fact is that the two objectives require fundamentally different assignment methods within the same network for the same demand. This fact can be illustrated with a mathematical process - for the simple network shown in Figure 1, based on a simplified version of the Bureau of Public Roads (BPR) delay function - by assigning a demand into the network and analyzing the resulting assignments for minimizing travel time and environmental production objectives. The BPR function given in Equation (1) is a generalized relationship between link flow and link impedance, which is the travel time in general.

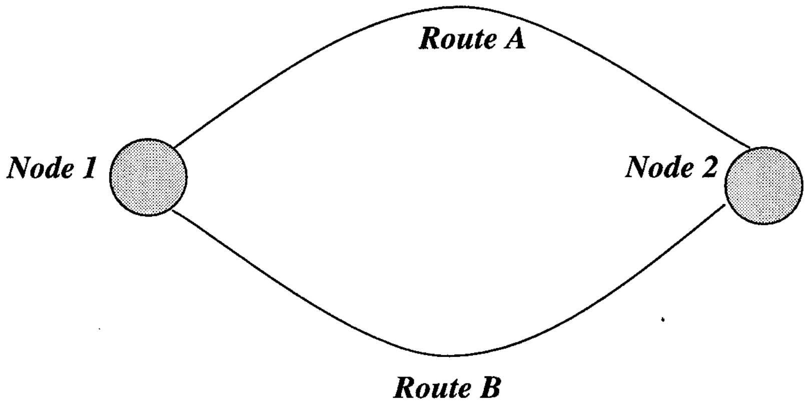

Figure 1: Simple Two-Route Network

Figure 1 above illustrates the configuration of a simple network that would be used here to demonstrate the assignment theory based on environmental and travel time objectives.

This sample network is made up of two one-way links (Routes A and B), and two nodes 1 and 2. The two links are assumed to have free travel times of 4 minutes and 6 minutes, respectively. Capacity on Route A is 2000 vehicles/hour, while capacity on Route B is 4000 vehicles/hour. The network is assumed to have a demand of 2000 vehicles/hour moving from Node 1 to Node 2. In order to demonstrate the effect of the assignment utilized in transportation planning functions the BPR (Bureau of Public Roads) function is used, which is expressed mathematically as follows:

$$T = w\left[1 + \alpha\left(\frac{q}{c}\right)^{\beta}\right] \qquad \textbf{(1)}$$

where

$T$ = impedance (or travel time) of a given link at flow $q$

$w$ = free-flow impedance of the link

$q$ = link flow

$c$ = link's capacity

$\alpha$ is a constant equal to 0.15 for planning purposes

$\beta$ is a constant equal to 4 for planning purposes

For simplicity of calculation we can assume that $\alpha = \beta = 1$ in which case the equation can be simplified as follows:

$$T = w(1 + \frac{q}{c}) \qquad \textbf{(2)}$$

Equation (2) demonstrates the principle of objective-based assignment. It is assumed that the objectives, treated here separately, are as follows:

1. Minimizing the travel time of the individual driver (or vehicle), known as user equilibrium;
2. Minimizing the total travel time of a set of vehicles traveling through a network within any given time period; and
3. Minimizing the total exhaust pollutants (e.g. Carbon Monoxide, Hydrocarbons and Nitrous Oxides) of a set of vehicles traveling through a network in any given time period.

## Equal Travel Time (User Equilibrium) Objective

Equal travel time objective is the most widely used objective in travel demand forecasting processes, which is based on Wardrop's (1952) first principle: minimizing the travel time of individual vehicles. It is assumed that an individual driver (vehicle) will choose the shortest path that will minimize his or her own travel time or impedance along any given route. From the network assignment standpoint, this means that all used paths between origin and destination nodes afford the same travel time, while all unused paths have times that are greater than the shortest time. Based on Equation (2) for Figure 1, the travel time on route A can be expressed as:

$$T_A = 4\left(1 + \frac{q_A}{2000}\right) = 4 + 0.002q_A\,(\text{mins.}) \qquad \textbf{(3)}$$

Likewise, travel time on route B can be expressed as follows:

$$T_B = 6\left(1 + \frac{q_B}{4000}\right) = 6 + 0.0015q_B\,(\text{mins.}) \qquad \textbf{(4)}$$

Also, the total demand can be expressed as

$$q_A + q_B = 3000 \text{ vehicles per hour, veh/hr} \qquad \textbf{(5)}$$

Solving Equations (3) and (4) simultaneously with Equation (5), we can find the assignment on both routes. Hence, $q_A = 1857$ veh./hr. and $q_B = 1143$ veh./hr. Substituting these assignment values back into Equations 3 and 4, respectively, results in equal travel time values for both routes A and B, where $T_A = T_B = 7.71$ mins. and a total travel time $Y$, for the network equal to 15.42 mins.

## Total Travel Time (System Equilibrium) Objective

The total travel time objective assumes that vehicles are routed along paths that would not necessarily reduce their individual travel times but rather minimize system-wide travel time as a whole. This assignment objective evaluates all possible paths and users (vehicles) are then assigned in order to minimize network wide travel time. Adding total travel times for each route for all vehicles derives an expression for the total travel time for the network. This expression is stated as follows:

$$Y = (4 + 0.002q_A)q_A + (6 + 0.0015q_B)q_B \qquad \textbf{(6)}$$

where Y is the total system time. Therefore, substituting for $q_B$ from Equation (4), then

$$Y = 0.0035q_A^2 - 11q_A + 31500 \qquad \textbf{(7)}$$

Next, minimizing Equation (7) we get $q_A = 1429$ and $q_B = 1571$ as the assignments over routes A and B, respectively. Finally, substituting these values in Equations (2) and (3), respectively, the travel times on both routes are now different. $T_A$ = 6.86 mins., while $T_B$ = 8.36 mins. Again, minimum total travel time $Y$ is calculated by simply adding travel times of all routes ($T_A + T_B$), which is equal to 15.22 mins. and can be compared with the total travel time of the user equilibrium objective, 15.42 mins.

## Minimizing Total Emissions

Here, in order to examine the assignment for emissions objectives consider Carbon Monoxide (CO) emissions. The formula for the CO aggregate emission rate for each individual vehicle as suggested by Yu (1997) is as follows:

$$CO = e^{-2.2182+0.03u-0.0184a} \text{ gals.} \tag{8}$$

Where $u =$ instantaneous speed,

and $a =$ acceleration.

Assuming a constant speed, then $a$ in Equation (8) = 0, hence we have:

$$CO = e^{-2.2182+0.03u} \text{ g/s/veh} \tag{9}$$

Since $u = link\_length, s \div time$, we can express Equation (9) as follows:

$$CO = \frac{se^{-2.2182+0.03u}}{u} \text{ (g/link/veh)} \tag{10}$$

Therefore, the total CO emission produced over routes A and B can be expressed as follows:

$$CO_{A+B} = \left( \frac{S_A e^{-2.2182+0.03\frac{s_A}{4+0.002q_A}}}{\frac{S_A}{4+0.002q_A}} \right) q_A + \left( \frac{S_B e^{-2.2182+0.03\frac{s_B}{6+0.0015q_B}}}{\frac{S_B}{6+0.0015q_B}} \right) q_B \tag{11}$$

$$\Rightarrow q_A(4+0.002q_A)e^{-2.2182+0.03\frac{s_A}{4+0.002q_A}} + q_B(6+0.0015q_B)e^{-2.2182+0.03\frac{s_B}{6+0.0015q_B}} \tag{12}$$

Assuming $S_A = S_B = 50$, then Equation (12) can then be minimized with a numerical method, which gives $q_A = 1500$ and $q_B = 1500$. Therefore, using Equations (3) and (4) once more we find that $T_A$ = 7mins., $T_B$ = 8.25mins., and $Y$ = 15.25 mins.

The following Table 1 summarizes the foregoing results for the network based on the three objectives. Considering the table, it is evident that assignments over the two routes are different for different objectives. Emission totals are also different for each objective. It should be noted, therefore, that route assignments would ultimately affect traffic flow, which in turn affects vehicle speeds.

Table 1: Route Assignment for Different Objectives

| **Operational Objective** | **Assignment Results** | **Route Travel Time** | **Total Travel Time** | **Total CO Emissions** |
|---|---|---|---|---|
| ***User Time*** | $q_A = 1857$ | $q_A = 7.71$ | Y = 15.42 | V = 3058.49 |
| | $q_B = 1143$ | $q_B = 7.71$ | | |
| ***Total Time*** | $q_A = 1429$ | $q_A = 6.86$ | Y = 15.22 | V = 3036.35 |
| | $q_B = 1571$ | $q_B = 8.36$ | | |
| ***Emissions (CO)*** | $q_A = 1500$ | $q_A = 7.0$ | Y = 15.25 | V = 3030.41 |
| | $q_B = 1500$ | $q_B = 8.25$ | | |

Because emissions and travel times display different sensitivities to speed, it is important to develop different traffic control and/or management strategies that would take this relationship into account and thus be more effective in minimizing emissions.

## Concept of Traffic Control, Assignment and Simulation Models

The foregoing explanation of the effects of different objective based assignments is important as it helps to explain the reason for the use of specific traffic control strategies in seeking travel time enhancement as well as environmental pollution mitigation. It is also important to understand the uses and effects of traffic controls, in particular, which are considered to be such methods and/or devices used in traffic networks to manipulate vehicle flow either for the purpose of achieving some environmental goal or enhancing the quality of network travel, or both. In many instances, though, the two objectives are not achieved simultaneously or with the same set of strategies. For the purpose of better understanding the principles of modeling traffic networks to analyze emissions and travel time, the following sections outline the concepts of traffic controls, assignment, and simulation models.

## Traffic Control

Traffic controls in use today consist, essentially, of traffic signals, ramp metering, changeable message signs, and traffic calming features like speed bumps. By far, the most widely used, and the most effective method of traffic control is the traffic signal. It is for this reason that the effects of traffic signal manipulation are being simulated in this research to explore the concept of environmental mitigation strategies.

Traffic control signals have direct effects on emissions levels because they influence the vehicles' modal events, which can be described as periods of acceleration, deceleration, cruise, and idle. The duration of these periods can be influenced by adjusting the length of cycle times of individual signals, simultaneously or sequentially, adjusting the red/green time split, and/or varying the number and locations of signals in a network. Any modeling emission-based objective method employed, therefore, will have to incorporate some combination of these options, which have the capability to directly factor in the variables of modal activity previously identified.

## Assignment/Simulation Models

The specific effects of traffic signal manipulations on pollutants and fuel consumption are measured today using various computer models and mathematical calculations. These models can be described as emission factor models that integrate specific aspects of traffic assignment and/or traffic simulation.

Traffic assignment can be described as the process of routing vehicles through a traffic network based on some specific equilibrium objective. As was demonstrated earlier, these objectives can include system-wide or individual travel time, or emissions reduction. As discussed earlier, traffic assignment methodologies, traditionally, have focused on the travel time equilibrium for both individual and system wide concerns.

Traffic simulation is an important method of experimentation and evaluation and incorporates the methodologies of network assignment. By using traffic simulation models, the relationship between vehicle speed profiles, which are the effects of different traffic control strategies, and emission levels can be reasonably demonstrated. In general, simulation models combine characteristics of a vehicle's modal activity and emission factors to derive emission output under certain driving conditions. Table 2 presents an overview of some of the assignment and simulation models in use today. A comparison of a few of these models and an overview of the DYNAMIC model is presented in Chapter 2.

Table 2: State-of-the-Art Models and Their Features

| **MODELS** | **Assignment** | **Simulation** | **Emissions** |
|---|---|---|---|
| **Static** | QRS II, EMME/2, TRANPLAN, all combined with EMFAC in emission estimation | TRANSYT 7F, NETSIM, CORSIM | MOBILE 5a, EMFAC, Modal emission models |
| **Dynamic** | DYNAMIC, DYNASMART, INTEGRATION | | DYNAMIC, INTEGRATION |

## Static vs. Dynamic Assignment

This section explains the basic differences between static and dynamic assignments. These concepts are very important in the modeling functions employed by researchers and planners.

If one considers a link, static assignment implies that at any instant in time the inflow traffic volume to the link is equal to the outflow volume. Further, it is understood that flows exist simultaneously on all links that make up a network path.

For the dynamic traffic assignment, however, inflow traffic volume is not necessarily equal to outflow volume for any given link. In fact, in a dynamic assignment, link load is considered to be variable. Link load is understood to be the number of vehicles present on a link at an instant of time (or during a time period), according to Jayakrishnan et al. (1995). Further, assignments based on traffic loads (dynamic assignments) directly translate to more sensitive formulation, which consider the dynamics of congestion. Static assignment uses a traffic flow variable, which does not accurately reflect flow/speed relationships. It is widely known that a given flow rate can have two corresponding speeds: high speed and low speed under congested conditions. It is important to understand, therefore, why the dynamic principles of traffic assignment are used in modeling network behavior in this research.

## Objective of this Research

Operational traffic control strategies employing the use of traffic signals, ramp metering, traffic incident management and changeable message sign controls determine the number of vehicle stops, which in turn, characterize the average modal event experienced in a given network. The research by Yu and Stewart (1995) has shown that the magnitudes of vehicle emissions are heavily affected by the distribution of these modal events; while on the other hand; the travel time factors are affected by vehicle average speed.

With this understanding therefore, the objective of this research is to demonstrate, by using the DYNAMIC traffic assignment/simulation model, the conceptual relationship between traffic control strategies and potentially harmful vehicle emissions. The dynamic traffic assignment and simulation, as opposed to the static method of modeling, is used in order to be more representative of the time series of vehicles' modal events and, thus, more accurately estimate the impacts of alternative traffic control scenarios on various travel time and environmental factors including pollutants and fuel consumption. Subsequently, this paper tries to demonstrate that emission or fuel consumption reduction is not necessarily achieved through the same traffic control techniques that are usually employed for reducing travel times.

The selected dynamic traffic assignment approach can quantitatively estimate the distribution of vehicles' modal events which consist of periods of acceleration, deceleration, cruise and idle, which can then be used for estimating the amounts of fuel consumption and emissions. These quantities can then be used for analytical comparison and, thus, as a basis for deriving optimum mitigation strategies.

# CHAPTER 2

## LITERATURE REVIEW

Essentially, three major mobile source-related emission constituents have been identified as hazardous to environmental quality. These constituents are Hydrocarbons (HC), Carbon Monoxide (CO), and Oxides of Nitrogen ($NO_X$). It would be helpful here to present a few of the traffic and emission models used in estimating levels of these vehicle pollutants. This chapter will also include a description of the DYNAMIC model, which is used in this research, and the basic features, and limitations of the other models in the context of objective-based evaluation.

### Traffic and Emission Models

Transportation emission estimation models generally combine the elements of traffic assignment values and emission rates based on variables such as vehicle type, speed profiles and climatic conditions. Therefore, emission models are designed to estimate emissions as a function of network route assignments and emission factors. These two elements are sometimes integrated into a single model like INTEGRATION or DYNAMIC. Alternatively, dedicated emissions models using inputted assignment values are also used to estimate emission quantities.

Currently, there exist two static emission factor models being used in modeling and estimation of the environmental pollutants mentioned previously. These models are MOBILE5a and EMFAC, and, as mentioned earlier, they both use as their basis of evaluation, vehicle average speed as the sole descriptor of the vehicle's modal events.

## Static Models

The MOBILE 5a Model. MOBILE 5a provides the user with an analytical tool to estimate emissions inventories for air quality planning. Essentially, the model determines emissions factors by modifying the input data to account for various conditions and factors that ultimately affect the overall inventory.

The user shapes specific scenarios by varying the parameters of such input data as average speed, ambient temperature, mileage accumulation, fuel types, and operating modes. These parameters are set in three distinct sections of the input data, i.e. Control Section, One-Time Data Section, and Scenario Section. The user has the option to modify the sample input files supplied with the model or to create new input files based on the specific characteristics of a given analysis.

Once again, the drawback to this model in estimating emission levels is that it cannot accurately measure the effect of traffic flow on emissions. As mentioned above, MOBILE 5a factors average speed as the determinant of a vehicle's modal characteristics. In reality, a vehicle's travel through a network is defined by a combination of modal activities discussed earlier.

The EMFAC Model. EMFAC is an emission factor model, which was developed by the California Air Resources Board (CARB) and the California Department of Transportation (Caltran). The major difference between EMFAC and MOBILE5a is that EMFAC uses thirteen vehicle combinations of vehicle classes and technology groups whereas MOBILE uses just eight.

The user-defined input data to EMFAC comprise of the calendar year, which is any year from 1970 through 2020, the model year, model year groups, either summer or winter season, speed range (3 – 65 mph), temperature range ($30^0$ to $110^0$ F), Inspection and Maintenance (I/M) program on or off and the desired output report.

## Dynamic Models

Dynamic models employed in the estimation and analysis of fuel consumption and vehicle emissions use as the basis for their computations, the four distinct modes of vehicle travel. These modes are acceleration, deceleration, cruise, and idle. Based on the dynamic traffic assignment principles adopted in this paper, the separate events of acceleration and deceleration can be defined as the range of instantaneous speeds of a vehicle coming to a full stop and then moving off again. This action implies a deceleration from cruise speed then, after a period of idle – depending on the nature of the stop event – there is a resumption in motion of the vehicle, implying a period of acceleration to cruise speed. Essentially, the motion of any given vehicle travel throughout a network will consist of proportionate periods of all four travel modes. These four travel modes relate more explicitly to the variables that affect vehicle emissions and fuel consumption.

The INTEGRATION Model. INTEGRATION is a dynamic traffic simulation model, which was developed for the analysis of problems related to the operation and optimization of integrated freeway and arterial traffic networks. This model estimates the emissions of a vehicle as it travel through a network influenced by real time traffic flows.

The emission estimation feature in INTEGRATION is a function of instantaneous speed and ambient temperature. It can estimate emissions for three vehicle classes, as well as the idling emission rates and cold start impact on emissions.

## Description of DYNAMIC

The DYNAMIC program was used in this research to analyze the environmental and travel time impacts of traffic control alternatives. The following is an overview of the operational elements of DYNAMIC.

DYNAMIC is a FORTRAN program that can dynamically assign a given traffic demand to a congested traffic network based on either of two travel time objectives discussed earlier, user and system equilibrium, or various environmental objectives. This program developed by Yu (1996), uses vehicle packets as the basic units in the traffic loading process. The traffic demands associated with each time slice for an Origin/Destination (OD) pair is organized into a number of packets. The size of a vehicle packet is dependent on the number of incremental steps assigned to the traffic demand for a given OD pair during a given time slice.

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

A vehicle's full stop can be described by deceleration from cruise speed to zero speed, whereas acceleration is considered a transition from full stop to a cruise speed or from a lower speed to a higher speed; deceleration implies the converse sequence of events. Any stops of the vehicle packets due to either over saturation or traffic signal effects will be desegregated into various acceleration and deceleration events. The number of stops caused by a traffic signal is estimated from the red time that is assigned to the approach link for a particular time slice.

DYNAMIC uses various algorithms to identify the number and distribution of the modal events, which in turn, are used to quantify fuel consumption and vehicle emission. It should be noted, once again, that any change in the network-wide traffic control and management strategies, such as traffic signal plans, would directly affect the distribution of vehicles' modal events, and therefore, the quantity of fuel consumption and emission levels.

The effect of various traffic signal plans is achieved in this examination, by placing traffic signals throughout a network within DYNAMIC and adjusting the cycle lengths through a range of 30 to 120 seconds. These cycle length adjustments are explained in more detail in Chapter 3.

# CHAPTER 3

## METHODOLOGY

Because there are no specific traffic models or management strategies currently available, which explicitly seek a reduction in vehicle emissions, it is necessary to first demonstrate the specific impacts of various traffic control strategies on vehicle emissions and fuel consumption as was developed in the preceding sections. This examination is important, as it will show that modeling algorithms currently used for optimizing travel time are not effective for optimizing emission and fuel consumption levels simultaneously. Secondly, this paper will present an analysis and comparison of emission quantities and travel times based on different objective functions for each using the DYNAMIC model.

The comparisons based on results generated by this program will attempt to show that traffic assignments are discreet for travel time objectives as opposed to environmental objectives. Subsequently, and more important, an attempt will be made to show that different traffic control strategies, through the manipulation of traffic signal timings (varying cycle lengths), will have significant impacts on vehicle emissions and fuel consumption for the same environmental objective.

Traffic signal control timings are adopted in this examination as the basis for modeling a general traffic control strategy, primarily because of the effectiveness of traffic control signal timings to define vehicular speeds throughout a given network. It is important to note that tailpipe emissions and fuel consumption have a direct relation to a vehicle's modal activity as defined by starts, stops, acceleration and deceleration and overall average speed. Adjusting traffic control signals, therefore, is a positive means of controlling traffic behavior within a network, which has the potential to affect environmental production levels. In other words, traffic signal timing is used as the basis for general traffic control strategies because of its inherent ability to define the overall modal activity of vehicle movement throughout a signalized roadway network.

The following describes the design of the traffic network and scenarios used to examine the relationships between traffic signal control timings and the resulting emission, fuel consumption levels and travel times. The description of the network is followed by a description of each of three scenarios examined. Chapter 4 then describes the results of each of the scenarios, respectively. The attributes of the network described here are inputted into DYNAMIC for the simulation.

## Network Design

Using as its basis the fundamental assignment theory illustrated earlier, a hypothetical network is designed to examine the effects of varying traffic signal timings on levels of emissions, fuel consumption and travel times. The network as shown in Figure 2 is designed to be generally representative of a typical real-world network consisting of a mix of one-way and two-way links meeting at common nodes. This simulated roadway network consists of eight nodes and twelve links. See Appendices 1 and 2 for the node and link input files respectively, which together describe the geometry of the network. Of the twelve links eight are made up of four pairs of two-way links. These link pairs are as follows: Links 2 and 9; Links 3 and 10; Links 5 and 11; and Links 6 and 12.

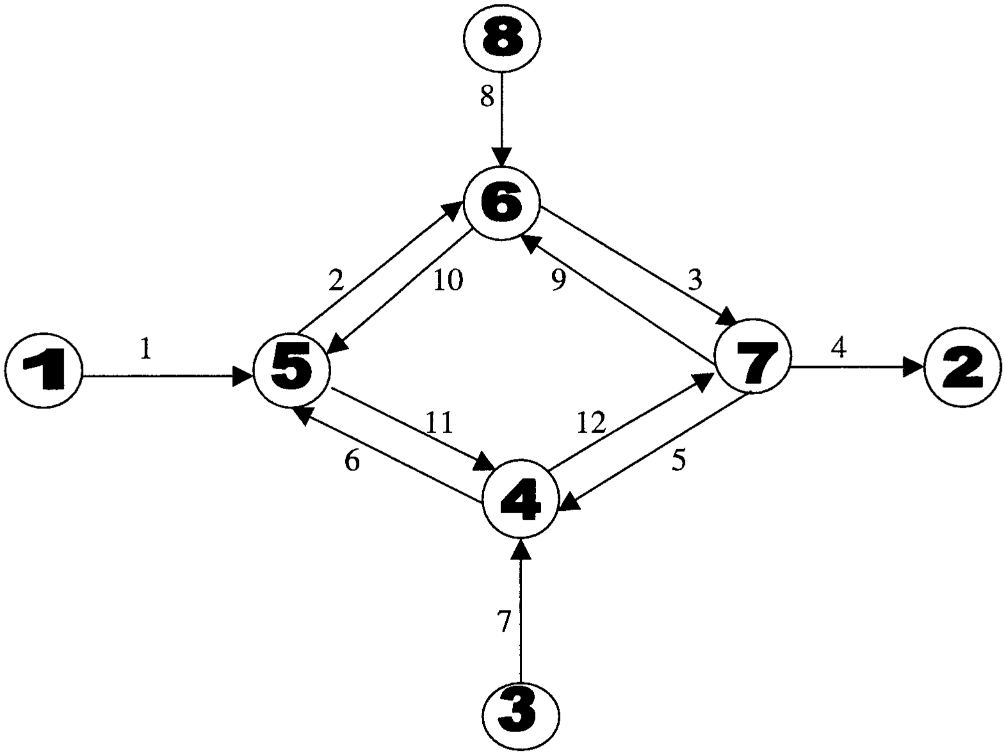

Figure 2: Hypothetical Network Used in DYNAMIC Simulation

All twelve links have identical capacities of 2000 vehicles per hour per lane. The links are also given identical lengths – 2 kilometers. The DYNAMIC model is designed to use metric units in its calibration. Traffic flow is assumed to move, from origin to destination, in the general direction from Node 1 to Node 2, with Nodes 3 and 8 serving as secondary sources of trip generation. Node 4 is a signalized intersection while Nodes 5, 6 and 7 are considered to be intermediate nodes or nodes that represent transitions in vehicle flows from one definite speed to another, for example, an on-ramp to a freeway. For simplicity, the free flow speed is assumed to be 60 kilometers per hour throughout the network.

## Design of Test Scenarios

Three basic scenarios are used to examine the behavior of emissions, fuel consumption and travel time variables against different operational objectives and traffic signal settings. These three scenarios are described below.

## Scenario One: Various Objectives vs. Emissions (Fixed Signal Timing)

The first scenario is an extension of the basic assignment principles described earlier, in Chapter 1. Here the attempt is to determine the differential levels of emissions, fuel consumption and travel times that would result from route assignments associated with the specific objectives of user time equilibrium, system travel time equilibrium, total vehicle emission, HC emission, CO emission, and $NO_x$ emission. As explained earlier, DYANMIC has the capability to model traffic simulations based on any of these six objectives.

In this scenario a single traffic signal is placed at Node 4 and its cycle length is held constant for the six different operational objectives: travel time (user time and total travel time), HC, CO, and $NO_x$ emissions, and fuel consumption. By holding the traffic signal timing constant for each of the objectives' simulation, only the effect of varying operational objectives becomes significant here. The network demand is assumed to be 2000 vehicles per hour per lane loaded from each of Nodes 1, 3 and 8 to Node 2. See Appendix 3 for details of the demand input file.

## Scenario Two: 1-Signal Network (Various Signal Settings Against a Fixed Operational Objective)

In this scenario the traffic signal timing is varied through a range of seven cycle periods to examine the resultant simultaneous effects on emissions, fuel consumption and travel times. The cycle periods range from 30 to 120 seconds in 10-second increments up

70 seconds then 90- and 120-second periods. The lost time of each cycle length is fixed at 5 seconds, which effectively increases the green time as the cycle length increases. The traffic signal is modeled to have two phases with phase 1 controlling approach Links 5 and 11 and phase two controlling approach Link 7. See Appendix 2 for the link input file.

Table 3: Cycle Lengths and Phase Splits

| **CYCLE TIME** *(secs)* | **PHASE 1** *(70%)* | | **Sub-Total** | **PHASE 2** *(30%)* | | **Sub-Total** |
|---|---|---|---|---|---|---|
| ▨ | ***Green Time*** | ***Lost Time*** | ▨ | ***Green Time*** | ***Lost Time*** | ▨ |
| **30(*.67*)** | 16(*.76*) | 5 | *21* | 4(*.44*) | 5 | *9* |
| **40(*.75*)** | 23(*.82*) | 5 | *28* | 7(*.58*) | 5 | *12* |
| **50(*.80*)** | 30(*.86*) | 5 | *35* | 10(*.67*) | 5 | *15* |
| **60(*.83*)** | 37(*.88*) | 5 | *42* | 13(*.72*) | 5 | *18* |
| **70(*.86*)** | 44(*.90*) | 5 | *49* | 16(*.76*) | 5 | *21* |
| **90(*.89*)** | 58(*.92*) | 5 | *63* | 22(*.81*) | 5 | *27* |
| **120(*.92*)** | 79(*.94*) | 5 | *84* | 31(*.86*) | 5 | *36* |

The phase split is set at 70% for phase 1 and 30% for phase 2, which is held constant through the range of cycle lengths. Table 3 illustrates the cycle lengths splits for the two phases for each cycle length.

In this scenario the user time objective is used over the range of signal timings since the traffic networks in reality, assign the traffic according to the traditional user time equilibrium principle. It becomes necessary, therefore, to evaluate the air quality and fuel consumption implications of alternative traffic control strategies based on a consistent user time equilibrium objective. The traffic signal in this scenario is kept at Node 4 and a constant origin to destination demand (OD) from Node 1 to Node 2 of 2000 vehicles per hour is modeled for all the signal settings.

## Scenario Three: 2-Signal Network

In the third scenario a second traffic signal is placed at Node 6. See Appendix 4. This traffic signal and the signal at Node 4 will use the same range of cycle lengths and phase splits as those used for the signal in the previous scenario. For the signal at Node 6 phase 1 will control Links 2 and 9 and phase 2 will control Link 8. See Appendix 5. Again, the network will be loaded with 2000 vehicles/lane/hour at each of the source Nodes 1, 3 and 8 to the destination, Node 2. Both signal timings will be simultaneously varied through the range used in the two previous scenarios, that is 30 seconds to 120 seconds with the same intervals. This scenario is used to compare emission and fuel consumption levels and travel times of networks with multiple traffic signal controls.

# CHAPTER 4

## RESULTS AND ANALYSIS

### Results of Scenario 1

The results of this examination, as illustrated in Figures 3, 4, 5 and 6, support the traffic assignment principles discussed previously, showing that the levels of vehicle emissions, fuel consumption and travel times change directly and independently for different operational objectives specified in the dynamic assignment. Recall that the operational objectives such as travel time (total and individual), fuel consumption, and fuel emissions (environmental pollutants) were each factored in as an independent operational objective of the traffic network. The resulting emission levels, therefore, are based on the simulated assignment for each objective.

Figures 3, 4 and 5 show that the total travel time objective produced generally higher levels of fuel consumption and emissions while the fuel consumption and $NO_x$ objectives produced the lowest levels of emissions and consumption. In general, travel time objectives render about two to five percent higher vehicle emissions than environmental objectives for fixed traffic signal timings within the same network. On the other hand, both user time and total travel time were highest for HC and fuel consumption objectives. Table 4 provides a summary of the results for Scenario 1.

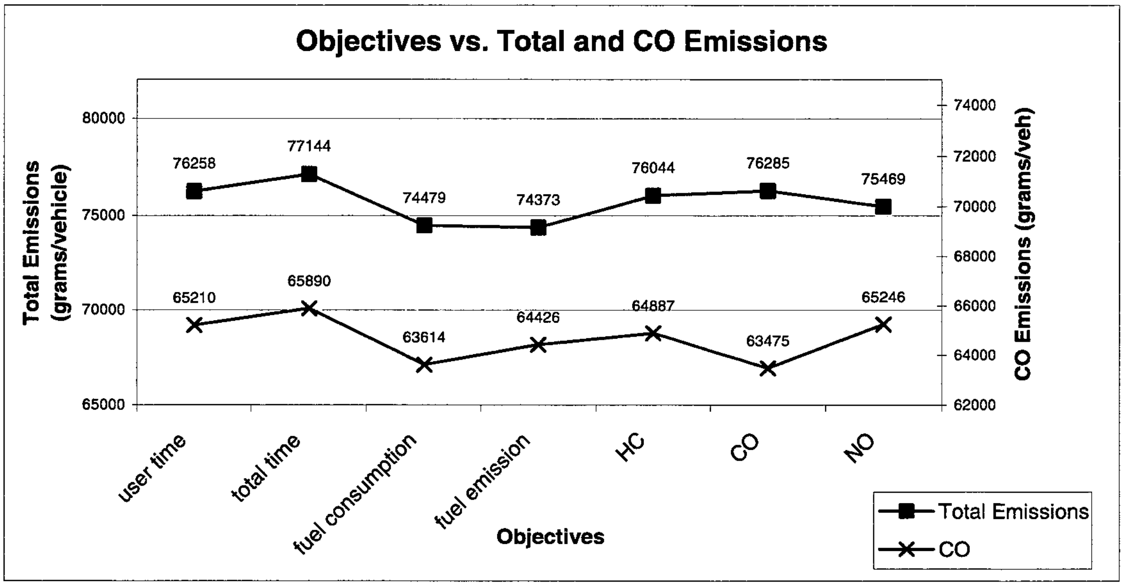

Figure 3: Operational Objectives vs. Total and CO Emissions

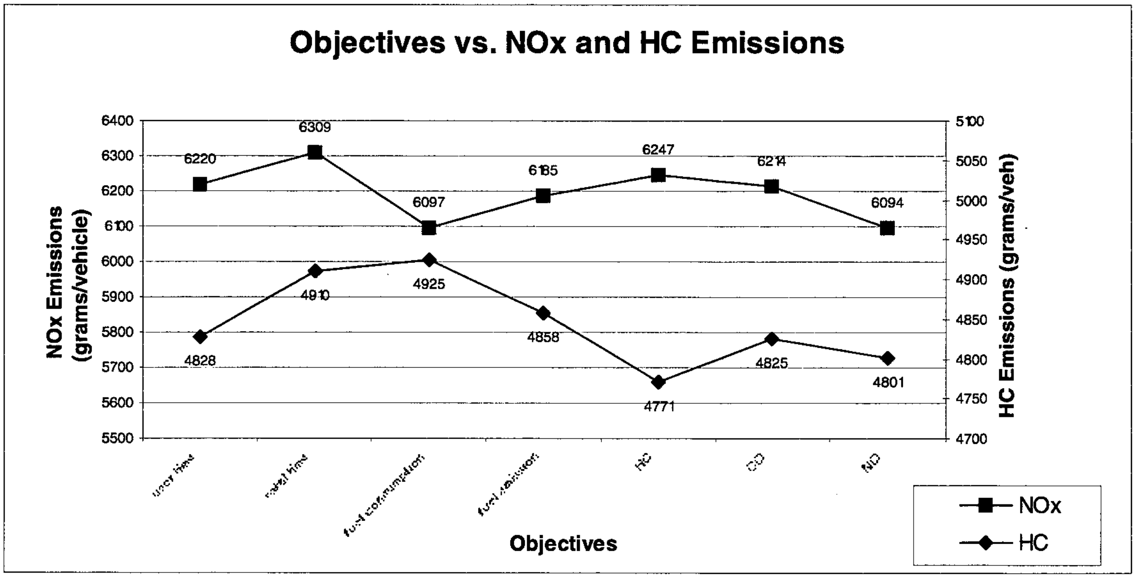

Figure 4: Operational Objectives vs. $NO_x$ and HC Emissions

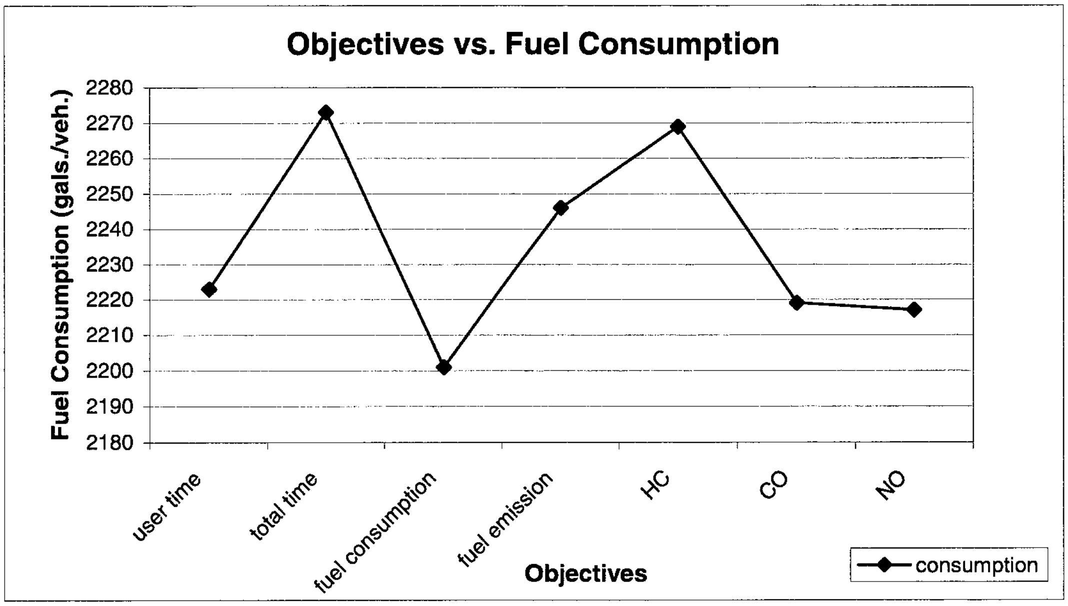

Figure 5: Operational Objectives vs. Fuel Consumption

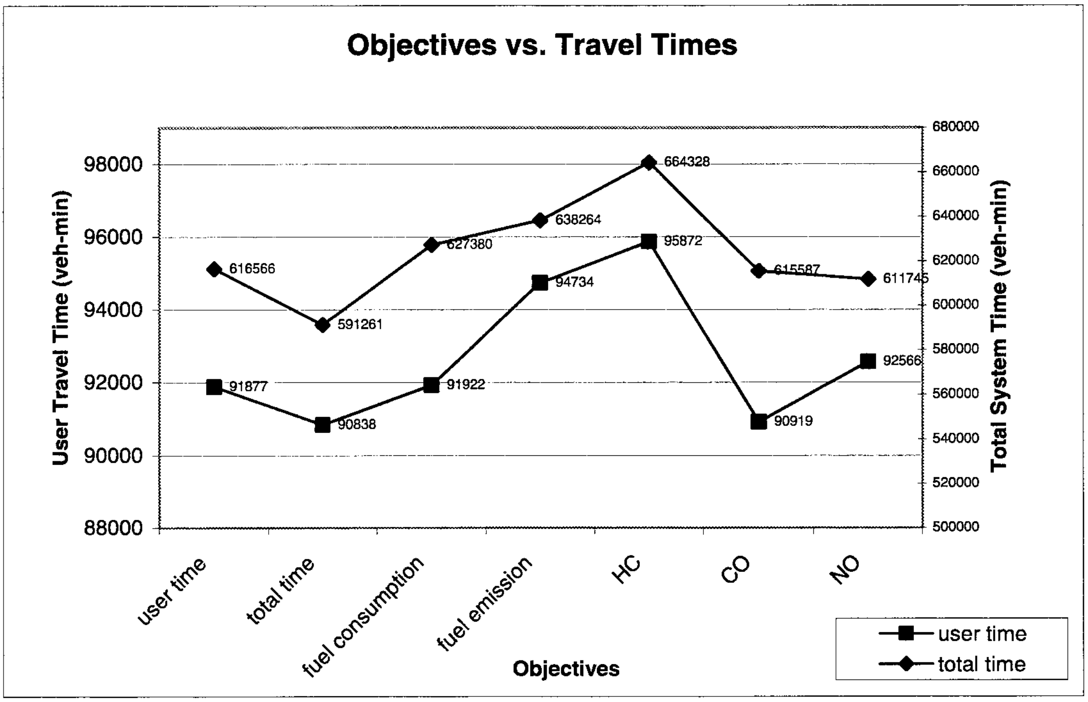

Figure 6: Operational Objectives vs. Travel Times

Table 4: Summary of Results

| Scenario 1 - 1-Signal Network (Multiple Objectives) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Objectives | Total Time (veh-mins) | User Time (veh-mins) | Consumption (gallons) | Emissions (grams) | CO (grams) | HC (grams) | Nox (grams) |
| User Equilibrium | 616566 | 91877 | 2223 | 76258 | 65210 | 4828 | 6220 |
| Total Time | 591261 | 90919 | 2273 | 77144 | 65890 | 4945 | 6309 |
| Fuel Consumption | 627380 | 91922 | 2201 | 74479 | 63614 | 4771 | 6094 |
| Fuel Emission | 638264 | 94734 | 2246 | 75469 | 64426 | 4858 | 6185 |
| HC | 664328 | 95872 | 2269 | 76044 | 64887 | 4910 | 6247 |
| CO | 615587 | 90838 | 2219 | 76285 | 65246 | 4825 | 6214 |
| Nox | 611745 | 92566 | 2217 | 74373 | 63475 | 4801 | 6097 |
| | | | | | | | |

| Scenario 2 - 1-Signal Network (Variable Cycle Length) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cycle Length (sec) | Total Time (veh-mins) | User Time (veh-mins) | Consumption (gallons) | Emissions (grams) | CO (grams) | HC (grams) | Nox (grams) |
| 30 | 3705547 | 106936 | 2419 | 80494 | 68617 | 5269 | 6609 |
| 40 | 2534249 | 102651 | 2389 | 80375 | 68583 | 5203 | 6589 |
| 50 | 2070413 | 101184 | 2363 | 79576 | 67914 | 5139 | 6524 |
| 60 | 1850420 | 100729 | 2356 | 79710 | 68058 | 5127 | 6525 |
| 70 | 1702509 | 99351 | 2345 | 79215 | 67630 | 5100 | 6485 |
| 90 | 1515122 | 99222 | 2322 | 78647 | 67162 | 5045 | 6440 |
| 120 | 1373955 | 98058 | 2300 | 76833 | 65540 | 4983 | 6311 |
| | | | | | | | |

| Scenario 3 - 2-Signal Network (Variable Cycle Length) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cycle Length (sec) | Total Time (veh-mins) | User Time (veh-mins) | Consumption (gallons) | Emissions (grams) | CO (grams) | HC (grams) | Nox (grams) |
| 30 | 7141600 | 126718 | 2757 | 92293 | 78683 | 6086 | 7524 |
| 40 | 4787731 | 116376 | 2700 | 91206 | 77818 | 5960 | 7428 |
| 50 | 3879875 | 112967 | 2683 | 90827 | 77517 | 5919 | 7390 |
| 60 | 3432052 | 110494 | 2670 | 90078 | 76853 | 5886 | 7338 |
| 70 | 3008734 | 108490 | 2650 | 89300 | 76353 | 5836 | 7288 |
| 90 | 2776934 | 107290 | 2630 | 89000 | 75600 | 5800 | 7258 |
| 120 | 2494206 | 106197 | 2619 | 88690 | 75704 | 5770 | 7216 |
| | | | | | | | |

## Results of Scenario 2

The preliminary results of Scenario 2, as shown graphically in Figures 7, 8, 9 and 10, show general decreases in travel times, fuel consumption and emission levels as the cycle length and effective green time is increased for the signal at Node 4. Figure 7 shows steady decreases in user and total travel time as the cycle length is increased from 30 to 120 seconds in the increments described earlier. It is significant that the total travel time shows a greater improvement of about 62% compared to just about 8% reduction in time for user equilibrium.

Figures 8, 9 and 10 also show decreases in fuel consumption and emission levels as the cycle length is increased. Notably, the rate of decrease is about the same for consumption and emissions as it is for user travel time (Refer to Table 4). Consumption and emission levels decreased by about 5% over the range of signal lengths. This implies that total travel time benefits most (in this network) with longer cycle lengths.

Notably, total emissions level actually decreases at the 60-second cycle length. This trend is noted for the levels of CO and $NO_x$ emissions specifically, while HC levels tend to flatten at the same cycle length. This would suggest that there maybe an optimum cycle length that would simultaneously minimize travel time and emissions.

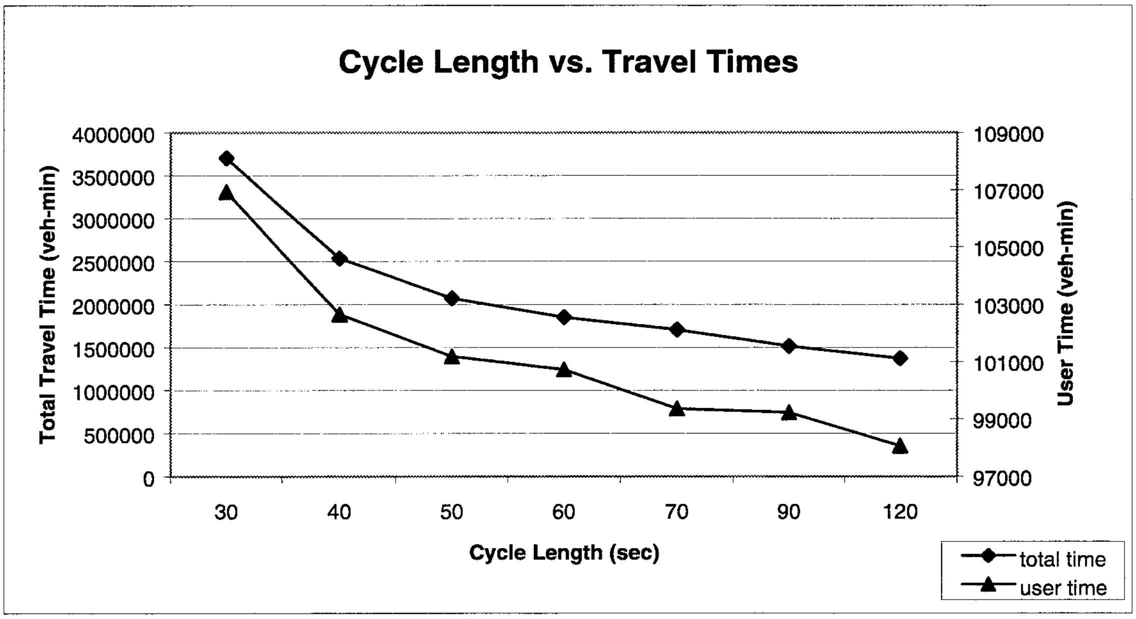

Figure 7: Cycle Length vs. Travel Times

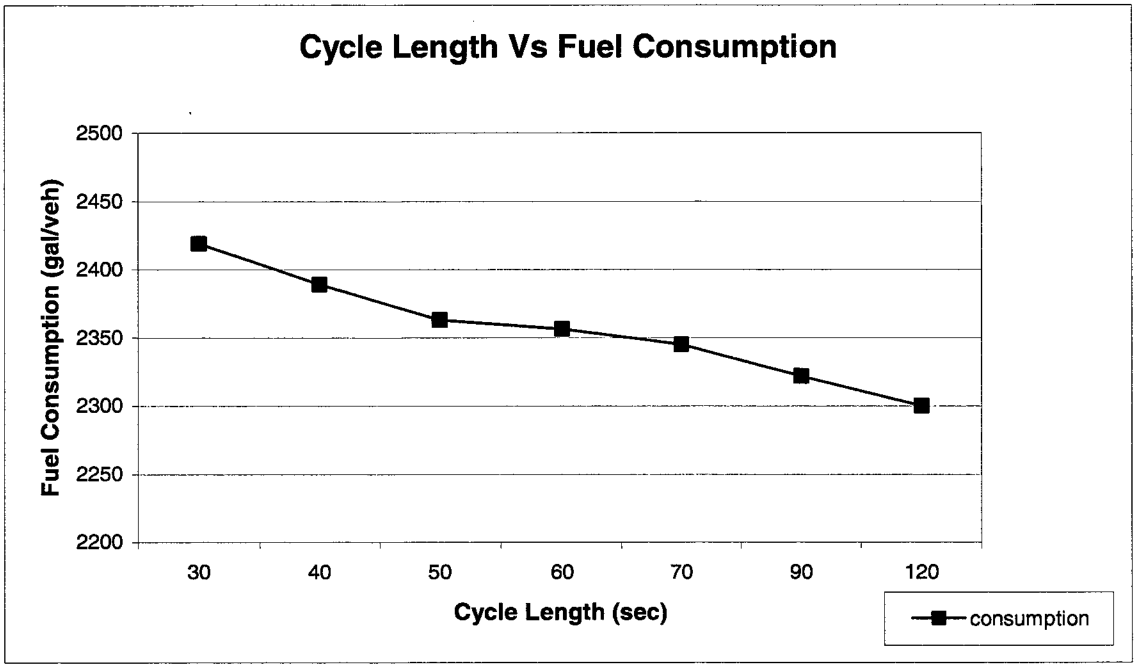

Figure 8: Cycle Length vs. Fuel Consumption

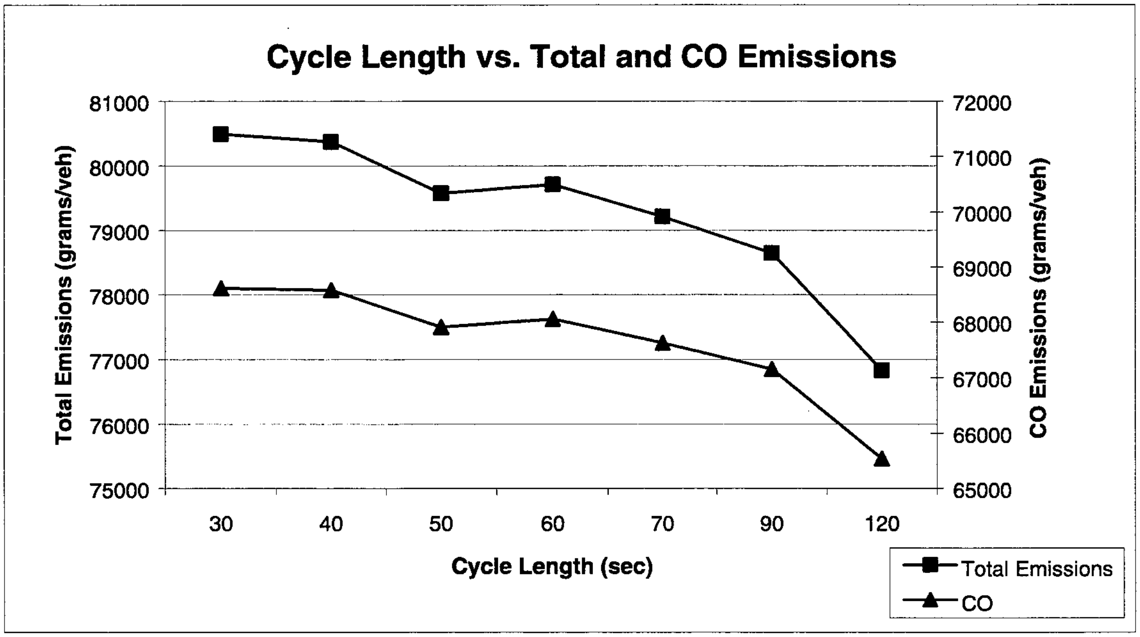

Figure 9: Cycle Length vs. Total and CO Emissions

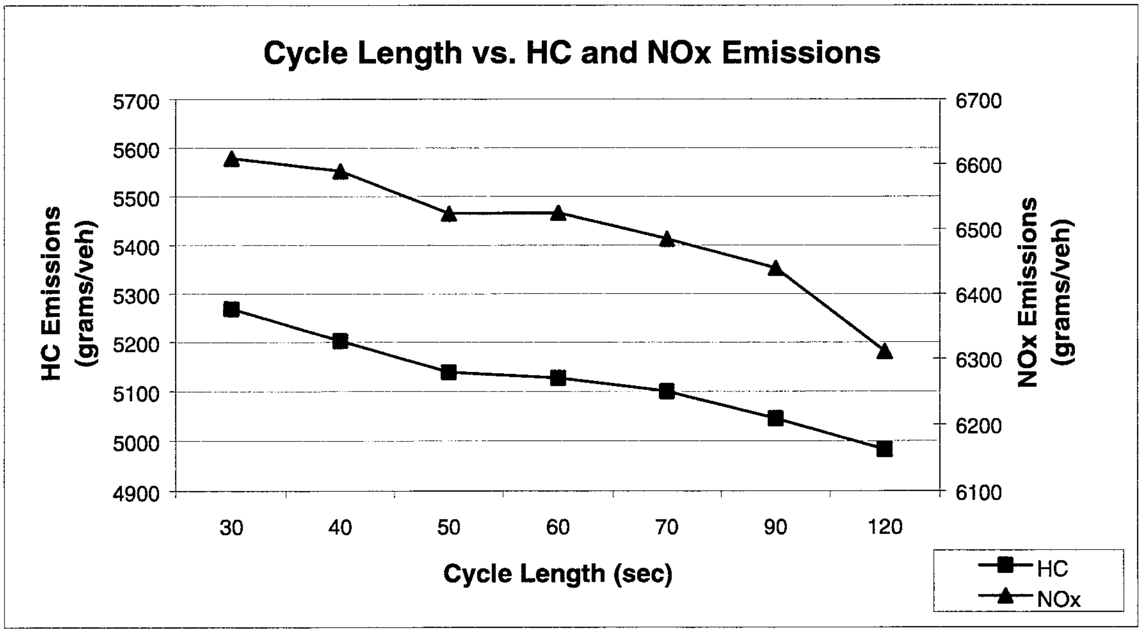

Figure 10: Cycle Length vs. HC and $NO_x$ Emissions

## Results of Scenario 3

Scenario 3 examined the effect once again on fuel consumption, tailpipe emissions and travel times, but this time by approximating the simulation of a more controlled network. Adding a second traffic signal to the network at Node 6 creates this effect. The results for this scenario can also be found in Table 4. Again, all the variables show decreases as the signal length increases. Figures 11 and 12 show the behavior of the fuel consumption and emission variables. As expected, with more restrictions to traffic flow, as a second signal placed in the network will create, vehicle performance is compromised resulting in greater fuel consumption and degradation of emission levels.

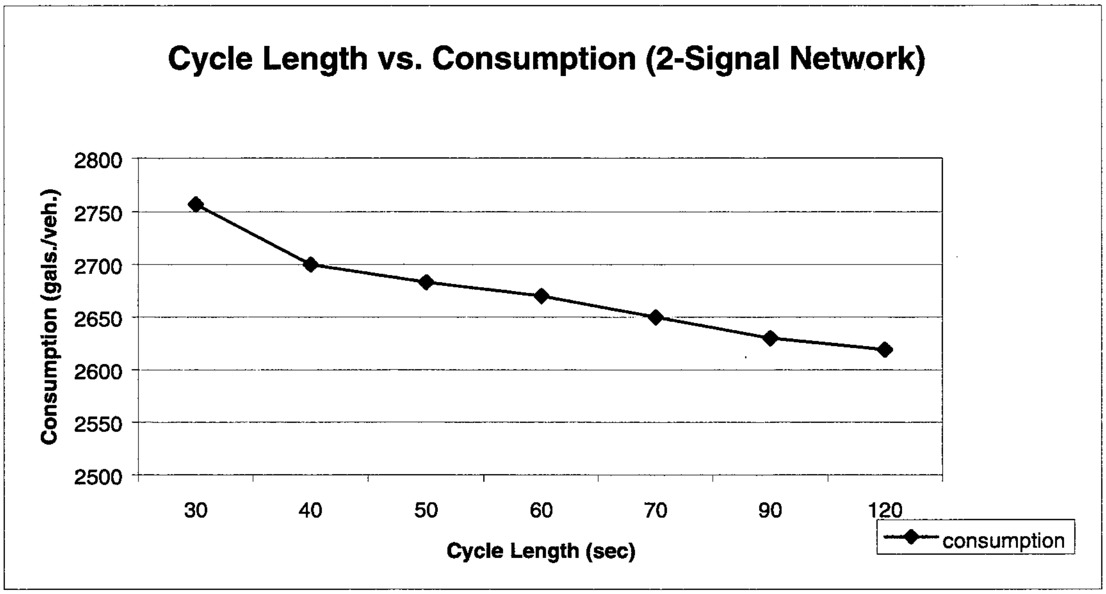

Figure 11: Cycle Length vs. Fuel Consumption in a 2-Signal Network

Figure 13 shows similar curves for travel times in the 2-signal network compared to the 1-signal network. What is more significant, however, is the difference in totals for the two networks. Further, there is less difference between the longer signal timings than between the shorter timings. At the 30-second timing the difference is about 92%, whereas at the 120-second timing the difference is about 80%. These variances are shown in Figure 14.

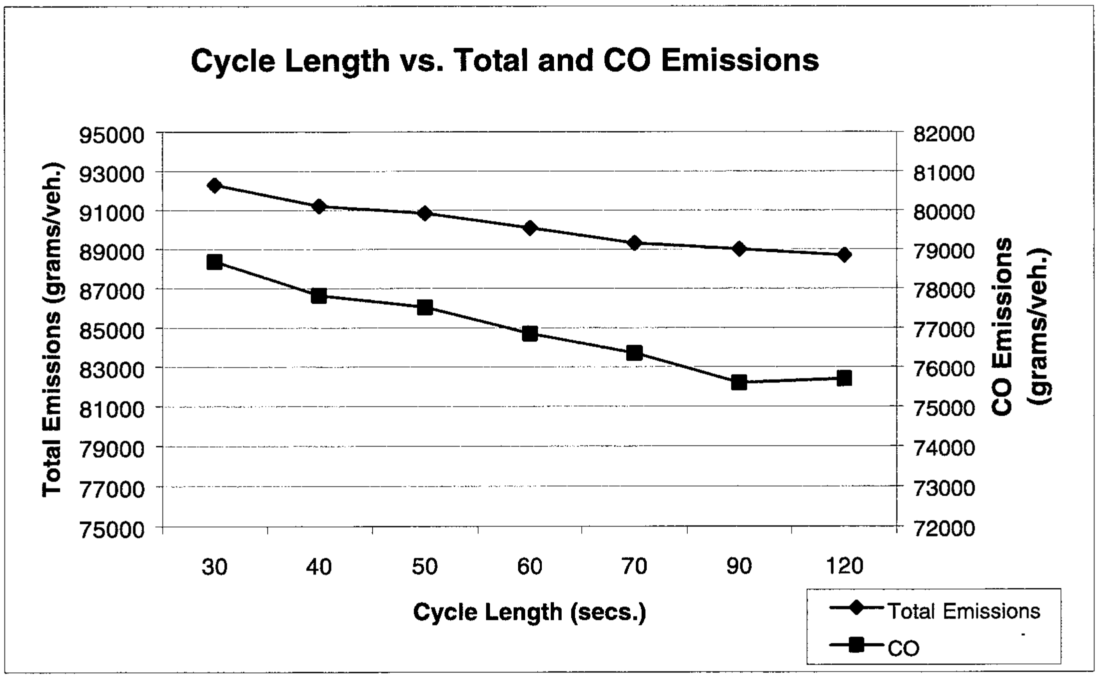

Figure 12: Cycle Length vs. Total and CO Emissions in the 2-Signal Network

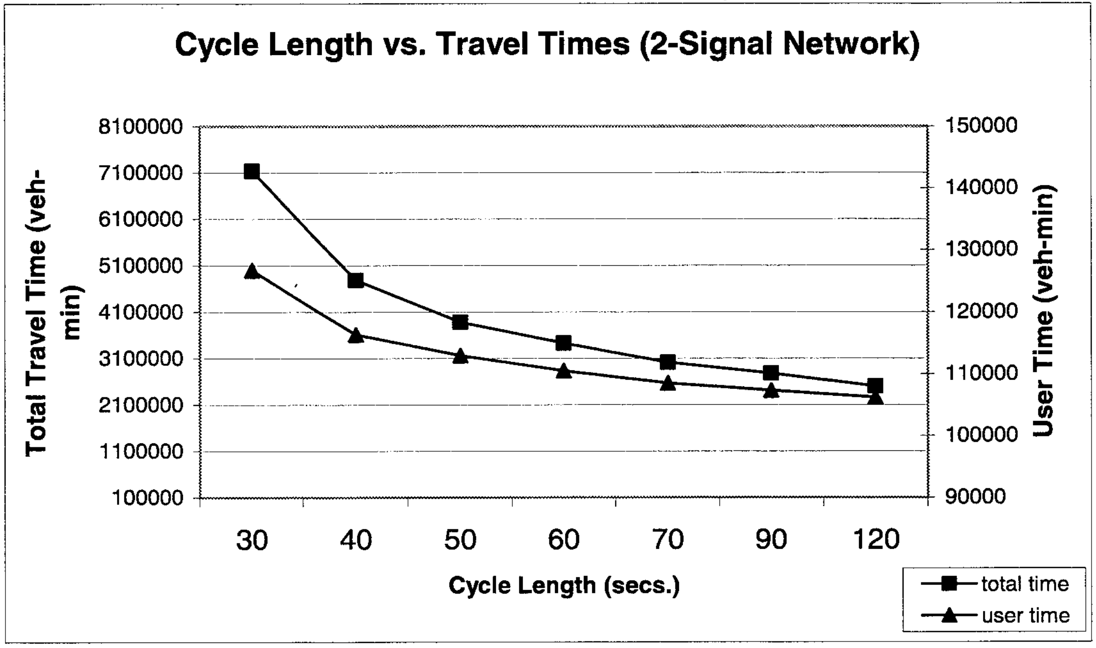

Figure 13: Cycle Length vs. Travel Times (2-Signal Network)

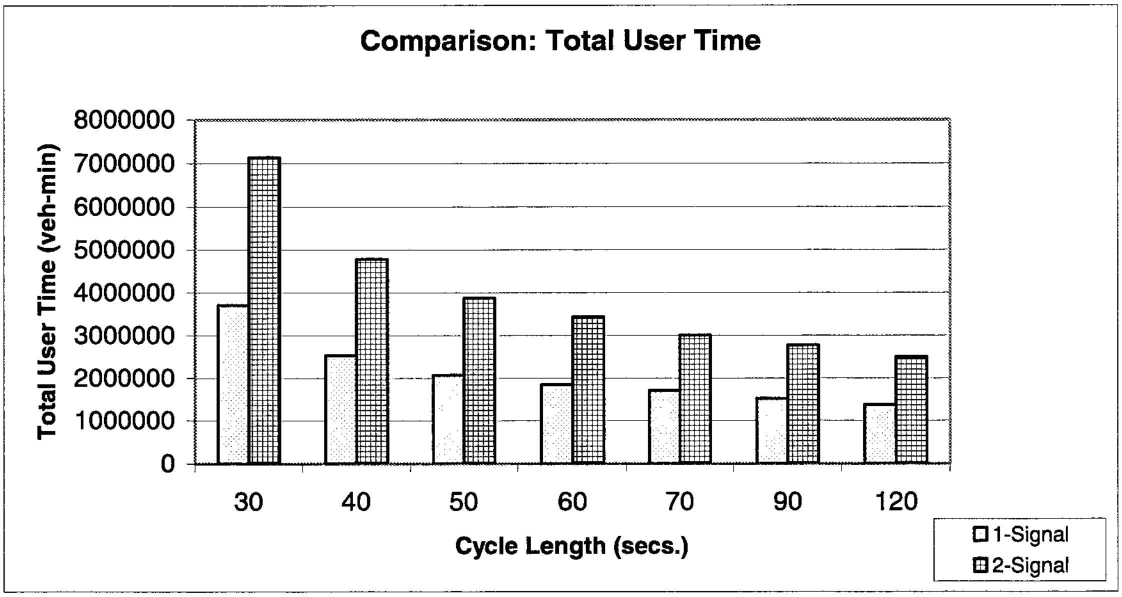

Figure 14: 1-Signal vs. 2-Signal (Total User Time)

On the other hand, the emission levels show relatively small changes between the two network scenarios. Both networks produced about 5% variation through the range of cycle timings. These results are shown in the bar charts in Figures 15, 16, 17, and 18. Additionally, Table 5 presents a brief comparison of the variables of the two networks for the shortest and longest cycle lengths.

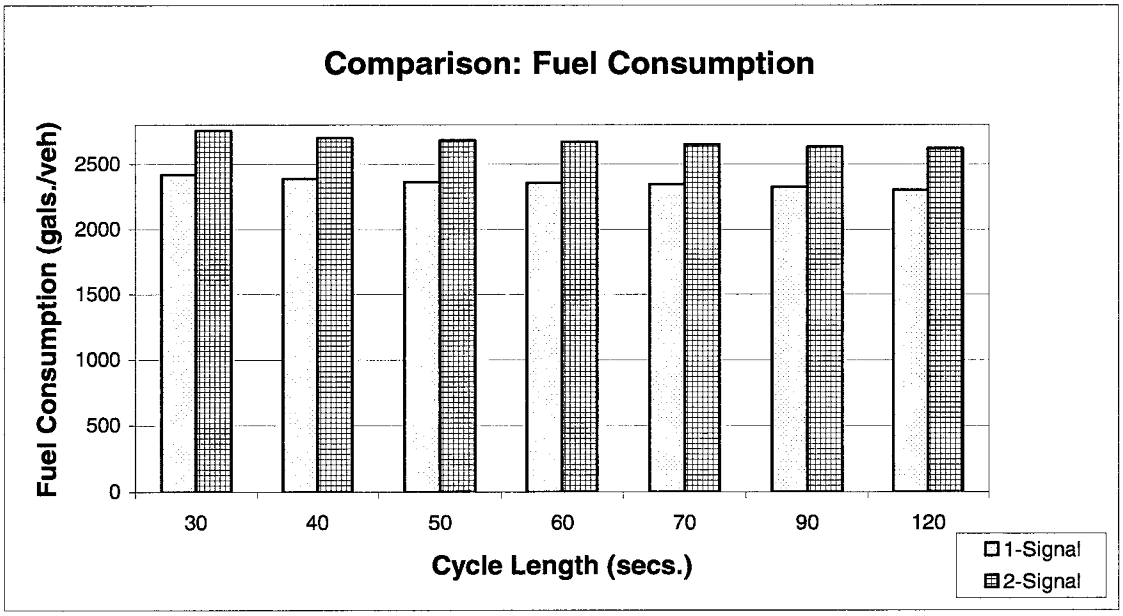

Figure 15: 1-Signal vs. 2-Signal (Fuel Consumption)

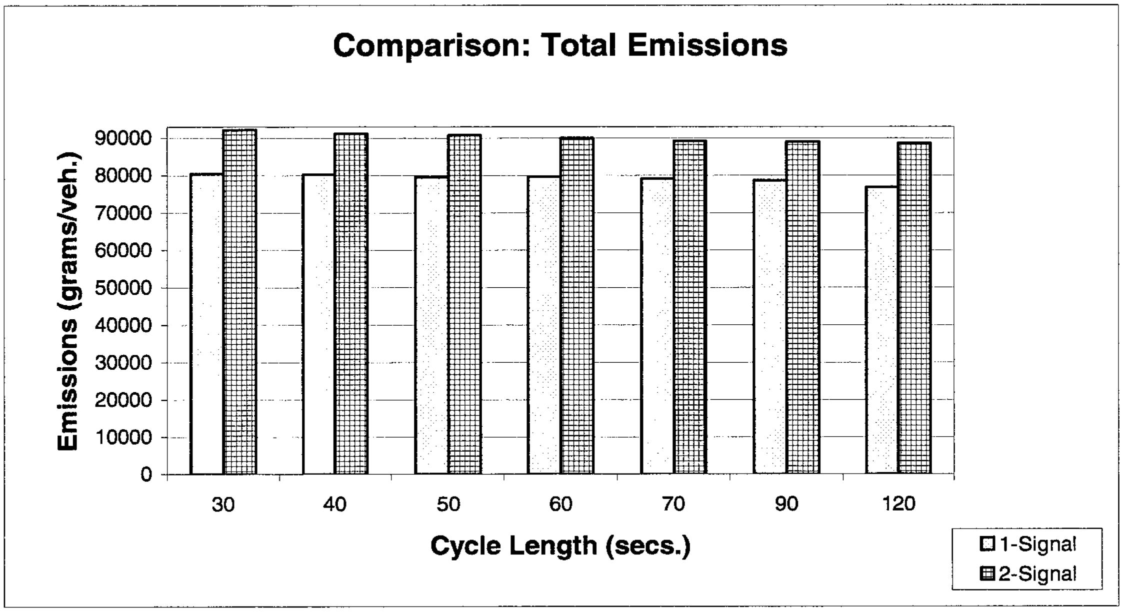

Figure 16: 1-Signal vs. 2-Signal (Total Emissions)

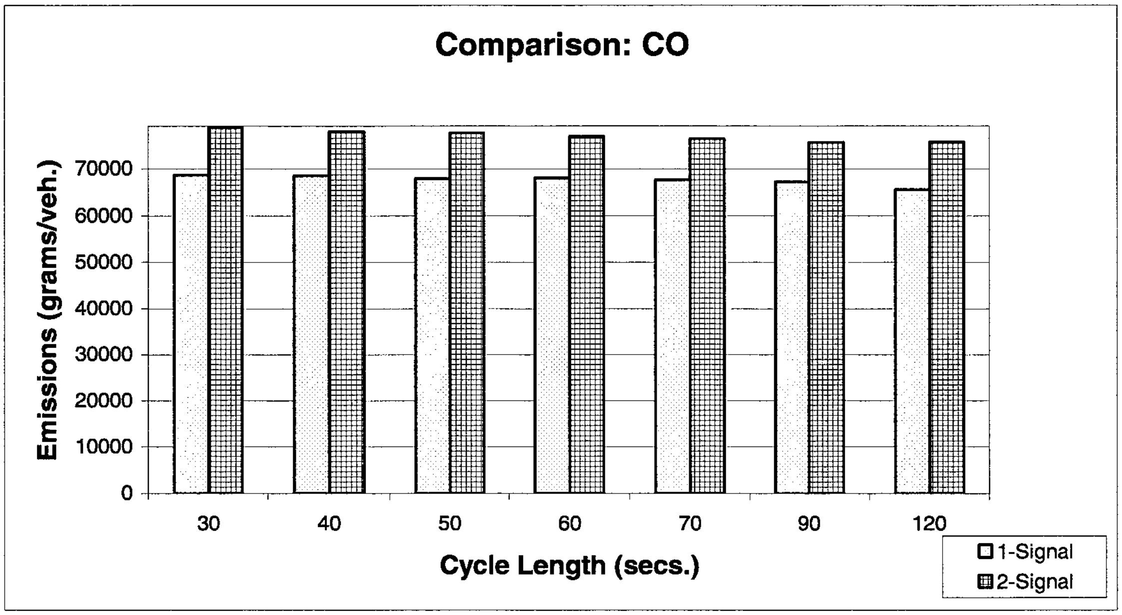

Figure 17: 1-Signal vs. 2-Signal (CO)

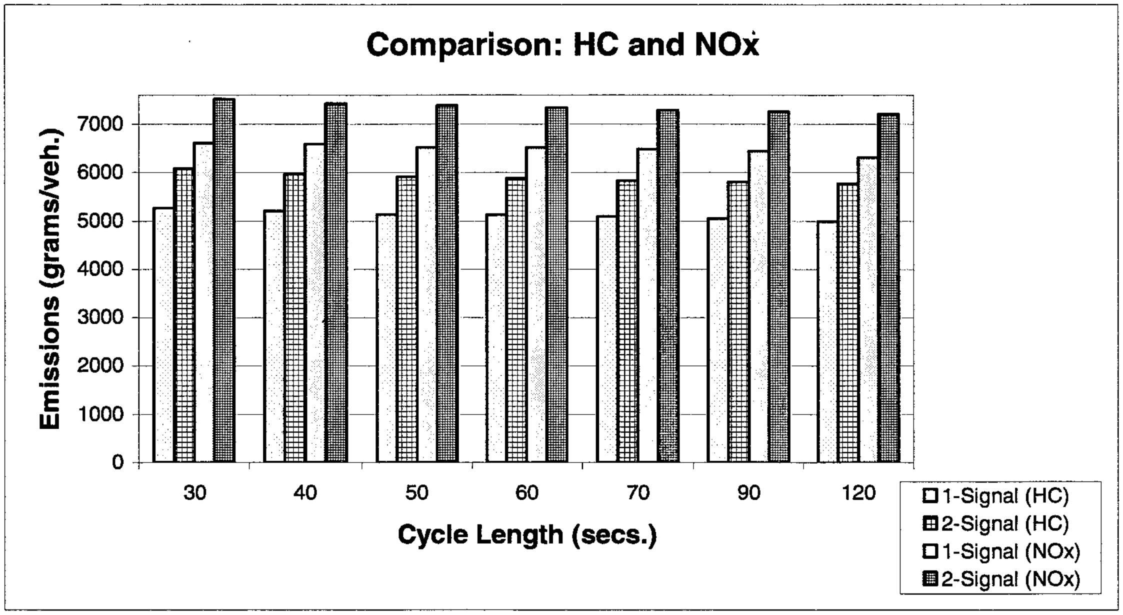

Figure 18: 1-Signal vs. 2-Signal (HC and $NO_x$)

The following Table 5 provides a comparison of fuel consumption, total emissions, total travel time and user travel time between the shortest and longest cycle lengths.

Table 5: Percentage Differences for the Two Networks (Shortest/Longest Cycle Lengths).

| | | | | |
|---|---|---|---|---|
| 30-Second | 1.4% | 14.7% | 92.7% | 18.4% |
| | Fuel Consumption | Total Emissions | Total Time | User Time |
| 120-Second | 1.3% | 15.4% | 81.5% | 8.3% |

It can be seen from the table that total time has the largest change between the two networks compared to the other variables, while fuel consumption showed the smallest variation between networks.

# CHAPTER 5

## CONCLUSION AND DISCUSSION

This research presented a conceptual examination of the relationships between operational objectives of a given traffic network and their resulting effects on the levels of production of environmental pollutants and simultaneous effects on system and user travel times. It also showed the resultant impact of varying traffic signal timings within a given network on environmental and travel time factors. The examination of these relationships is important to the transportation planning aspect because it helps to dispel the notion that the process of reducing travel times simultaneously reduces the production of environmental pollutants.

Based on the findings of this preliminary research, it thus can be concluded that first, the analysis of emissions modeling requires an explicit formula that takes into account its individual behavior compared to travel time based modeling. As previously outlined, models and formulas traditionally used in traffic assignment routines are not explicit enough to account for the various components of a vehicle's driving profile. It was found that the EMFAC and MOBILE 5a planning models in particular, factor a vehicle's average speed as their sole descriptor of the driving activity, which is not explicit enough to simulate real world driving conditions and, hence, can not accurately estimate emissions and fuel consumption levels.

Second, it can be concluded that traffic control strategies, at least through signal timings, is an effective approach to mitigating tailpipe emissions even though it may result in losing some travel time benefits. Recall the results of the tested scenarios where the effective red time or the time a vehicle is made to idle at a stoplight, shows direct relationships with environmental pollution levels.

Based on the results of this research, it can be concluded that the concept of using traffic signal controls to obtain certain environmental results is feasible. It is recommended, therefore, that further efforts be made to examine these basic relationships between tailpipe emissions and traffic signal manipulation. It is further recommended that the scenarios be structured within more complex, real-world networks that would offer the basis of a framework for developing optimum signal settings for improving network travel times while mitigating emissions productions. This follow-up research should also incorporate the examination of the effects of various phase splits in relation to the capacities and volumes of the links they control.

# APPENDIX

# APPENDIX I

Node Input File: Basic Network Configuration

```
8
1   1.0  4.0  3   0

2   7.0  4.0  2   0

3   4.0  1.0  1   0

4   4.0  2.0  4   0

5   2.0  4.0  4   0

6   4.0  6.0  4   0

7   6.0  4.0  4   0

8   4.0  7.0  1   0
```

# APPENDIX II

Link Input File: 1-Signal Network @ N4

```
12
1  1  5   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 1

2  5  6   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 2

3  6  7   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 3

4  7  2   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 4

5  7  4   2.0   60   2000   1   0   1.00  1.0   1   1   0  0  0  Link 5

6  4  5   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 6

7  3  4   2.0   60   2000   1   0   1.00  1.0   1   2   0  0  0  Link 7

8  8  6   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 8

9  7  6   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 9

10 6  5   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 10

11 5  4   2.0   60   2000   1   0   1.00  1.0   1   1   0  0  0  Link 11

12 4  7   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 12
```

# APPENDIX III

OD Input File: Origin - Destination Demand

```
3  1.0

1  1  2  2000  0    0   3600  1.0  0.0  0.0  0.0  0.0  0  1

2  3  2  2000  0    0   3600  1.0  0.0  0.0  0.0  0.0  0  1

3  8  2  2000  0    0   3600  1.0  0.0  0.0  0.0  0.0  0  1
```

# APPENDIX IV

```
Link Input File: 2-Signal Network(@N4 & N6)-Variable Signal Lengths-User
Time Objective

12
1 1  5   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 1

2 5  6   2.0   60   2000   1   0   1.00  1.0   2   1   0  0  0  Link 2

3 6  7   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 3

4 7  2   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 4

5 7  4   2.0   60   2000   1   0   1.00  1.0   1   1   0  0  0  Link 5

6 4  5   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 6

7 3  4   2.0   60   2000   1   0   1.00  1.0   1   2   0  0  0  Link 7

8 8  6   2.0   60   2000   1   0   1.00  1.0   2   2   0  0  0  Link 8

9 7  6   2.0   60   2000   1   0   1.00  1.0   2   1   0  0  0  Link 9

10 6  5   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 10

11 5  4   2.0   60   2000   1   0   1.00  1.0   1   1   0  0  0  Link 11

12 4  7   2.0   60   2000   1   0   1.00  1.0   0   0   0  0  0  Link 12
```

# APPENDIX V

Signal Input File: 2-Signal Network(@N4 & N6)-Variable Signal Length-User Time Objective

```
2  1  150
1
1  92  30  120  0  2  60  5  22  5  0

2  92  30  120  0  2  60  5  22  5  0
```

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