Available online at www.sciencedirect.com
ScienceDirect
Transportation Research Part D 13 (2008) 151–167
TRANSPORTATION RESEARCH PART D
www.elsevier.com/locate/trd

The effects of route choice decisions on vehicle energy consumption and emissions

Kyoungho Ahn [a], Hesham Rakha [b,*]

[a] Virginia Tech Transportation Institute, 7054 Haycock Road, Falls Church, VA 22043, United States
[b] Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech Transportation Institute, Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061-0536, United States

Abstract

Motorists typically select routes that minimize their travel time or generalized cost. This may entail traveling on longer but faster routes. This raises questions concerning whether traveling along a longer but faster route results in energy and/or air quality improvements. We investigate the impacts of route choice decisions on vehicle energy consumption and emission rates for different vehicle types using microscopic and macroscopic emission estimation tools. The results demonstrate that the faster highway route choice is not always the best from an environmental and energy consumption perspective. Specifically, significant improvements to energy and air quality can be achieved when motorists utilize a slower arterial route although they incur additional travel time. The study also demonstrates that macroscopic emission estimation tools (e.g., MOBILE6) can produce erroneous conclusions given that they ignore transient vehicle behavior along a route. The findings suggest that an emission- and energy-optimized traffic assignment can significantly improve emissions over the standard user equilibrium and system optimum assignment formulations. Finally, the study demonstrates that a small portion of the entire trip involves high engine-load conditions that produce significant increases in emissions; demonstrating that by minimizing high-emitting driving behavior, air quality can be improved significantly.

1. Introduction

Traffic congestion has grown significantly in the past two decades. A recent study found that the hours of delay in the U.S. increased by 528% (0.7–3.7 billion hours) from 1982 to 2003, and individual travelers spend about three times as many extra delay hours (16–47 h) than they did 20 years ago. Furthermore, congestion affects more roads, trips, and times of day in most US metropolitan areas (Schrank and Lomax, 2005).

Due to congestion, motorists face a difficult trip-planning process when attempting to reduce delays and improve travel time reliability. This decision-making process is based on the drivers' urgency, experience, and current information on travel time, trip distance, and other trip-related factors. However, energy and environmental impacts are not typically utilized in drivers' decision-making process. This paper attempts to

* Corresponding author.
E-mail address: hrakha@vt.edu (H. Rakha).

1361-9209/$ - see front matter
doi:10.1016/j.trd.2008.01.005

quantify the energy and environmental impacts of route choice decisions using in-field collected global positioning system (GPS) data and simulation results.

Motorists typically choose routes that minimize their travel cost (e.g., travel time). Therefore, drivers typically select longer routes if they produce travel cost savings. However, the question that needs addressing is whether taking a longer but faster route can result in energy and air quality improvements. This study investigates the impacts of route choice decisions on vehicle fuel consumption and emission rates using GPS data gathered during the morning commute near a suburb in the Washington, DC metropolitan area. The study analysis is further expanded by conducting a sensitivity analysis using the INTEGRATION microscopic traffic simulation software.

The objectives of this study are fourfold. First, the study investigates the impact of route choice on vehicle fuel consumption and emission rates. Second, the study compares microscopic and macroscopic emission estimation tools for routing choices. Third, the study evaluates the effectiveness of utilizing user-equilibrium (UE) and system optimum (SO) traffic assignments for environmental improvement and energy saving considerations. Finally, the paper investigates whether optimum routing strategies vary based on vehicle characteristics.

2. Overview of environmental impacts of traffic assignment

The commonly used UE and SO traffic assignment models typically utilize minimum travel time as a generalized cost to assign traffic flows over a network. However given that UE and SO assignments are estimated based on travel time, the fuel consumption and emissions of UE and SO conditions may not produce optimum energy and emission rates. Several researchers have investigated traffic assignment methods using environmental cost functions.

Tzeng and Chen (1993) developed the multi-objective traffic assignment method. They formulated multi-objective functions using nonlinear programming techniques and produced various solutions to emit low CO emissions. By utilizing the eigenvector weighting method with pair-wise comparison, the researchers estimated compromised solutions for the flow patterns. They applied the case study of metropolitan Taipei to evaluate the developed traffic assignment model, which utilized a simplified travel time function and CO emission module. The study utilized a fixed amount of CO emissions per link and the emissions were summed up across all vehicles on a link (Tzeng and Chen, 1993).

Rilett and Benedek (1994) and Benedek and Rilett (1998) investigated an equitable traffic assignment with environmental cost functions. They emphasized the impacts of CO emissions when UE and SO traffic assignments were applied to a sample network, a simple network from Ottawa, Ontario, Canada and a calibrated network from Edmonton, Alberta, Canada. The studies utilized a simple macroscopic CO emission model used in the TRANSYT 7F software. The emission model utilized the average speed and the link length as input variables. The researchers showed that the traffic flows of the SO–CO (the traffic flows that have the minimum CO emissions) condition were roughly equivalent to the flows of the UE and SO conditions within a small error range (Benedek and Rilett, 1998; Rilett and Benedek, 1994).

Sugawara and Niemeier (2002) developed an emission-optimized traffic assignment model that used average speed CO emission factors developed by the California Air Resources Board (CARB). The sample network case study concluded that emission-optimized trip assignments can reduce system-level vehicle emissions moderately when compared to the time-dependent UE and SO conditions. The research also found that the emission-optimized assignment is most effective when the network is under low to moderately congested conditions, saving up to 30% of CO emissions; when the network is highly congested, the emission reduction is diminished to 8%. The authors explain that under emission-optimized conditions, less traffic volume is assigned to the freeway because emission levels are very high at freeway free-flow speeds (Sugawara and Niemeier, 2002).

Nagurney and her colleagues developed a multi-class and multi-criteria traffic network equilibrium model with an environmental criterion and claimed that a desired environmental quality standard can be achieved by the proposed model through a particular weighting method. In the study, a fixed amount of CO emission rate per traveler per link was utilized to estimate the CO emissions (Nagurney, 2000; Nagurney and Dong, 2002; Nagurney et al., 1998).

As demonstrated, a number of researchers have focused on traffic assignment methods that can improve the environment. However, these research efforts have utilized simplified travel time functions and simplified mathematical expressions to compute emission rates based on average link speeds without accounting for transient changes in a vehicle's speed and acceleration as it travels. These approaches have been accepted by many researchers due to their simplicity; however, these methods are not adequate to quantify the energy and environmental impact of route choice behavior, particularly on congested networks, due to the significant transient behavior that is typical of such networks. To overcome the limitations of current research methods for evaluating the impact of traffic assignment, this study adopted microscopic fuel consumption and emission models using instantaneous speed and acceleration levels as explanatory variables.

3. Field data collection

3.1. Study corridor characteristics

To identify the energy and environmental impacts of route choice behavior, morning commute GPS data were collected in the Northern Virginia area. As shown in Fig. 1, the arterial route, VA Route 7, extends over 22.6 km (17.25 mi) and covers 32 signalized intersections. The study section started at the intersection of VA 28 (Sully Road) to the west and extended to the intersection of I-66 to the east. The corridor's entire length is divided, with a four-lane cross-section on the eastern side and a six-lane cross-section on the western side. The posted speed limits range from 56 km/h (35 mi/h) on the congested east side to 88 km/h (55 mi/h) on the west side.

The highway route connects two highway sections and two arterial sections as shown in Fig. 1. The highway section extends from the intersection of VA 28 (Sully Road) and Route 7 to the south and connects to a section of VA 267 (Dulles Toll Road) and a section of I-495 and finally connects to Route 7. The distance of the highway route is 35.85 km of which 22.56 km traverses highways (VA 267 and I-495). The arterial section of this route consists of a section of VA 28 that extends over 9.94 km and covers four signalized intersections and a section of Route 7, which is 3.35 km long and has six signalized intersections.

Traffic flows along the corridors are typically directional. During the morning peak, traffic along the study corridors generally moves eastbound, toward downtown Washington, DC and Fairfax, Virginia. The eastern portion of the study section, which has closely-spaced signalized intersections on VA 7, is typically more congested than other portions of the study section. The study corridors are controlled by a centralized, computerized signal system with an optimized cycle length of 180 or 210 s depending on the time of day. Most

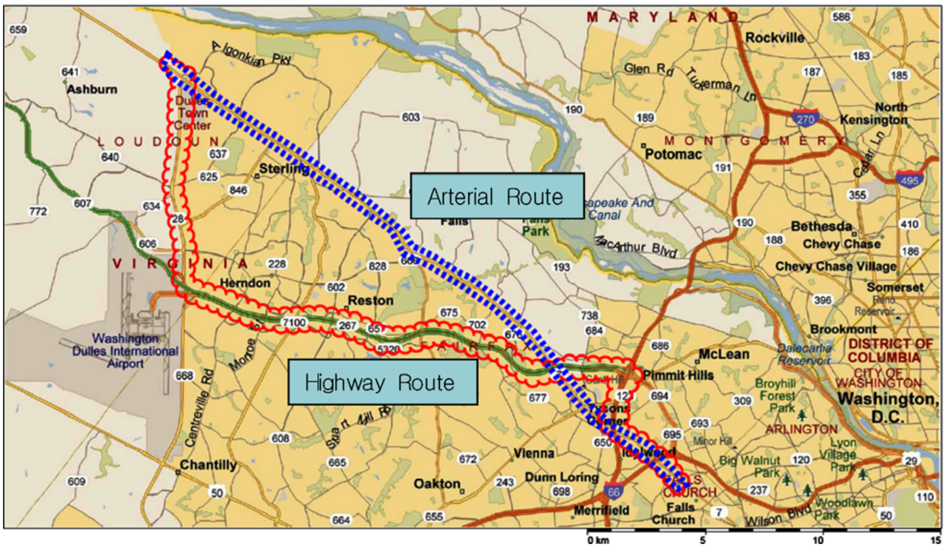


Fig. 1. Highway and arterial study corridors.

of the signal cycle time is assigned to the main route VA 7 and VA 28. The directional distribution of signal timing varies according to the time-of-day and, during the morning peak, more signal timing is assigned to the eastbound direction. These signal timings are continuously optimized by the Virginia Department of Transportation (VDOT) staff and thus represent the state-of-practice in optimal signal control. Since the study only investigates the impact of different route choices on vehicle fuel consumption and emission rates, a detailed description of the traffic signal operations on the study corridor is beyond the scope of the paper. The study utilizes GPS data collected under current traffic signal operations on the study sections during the morning commute period.

3.2. GPS data collection procedures

GPS technology is increasingly being used for transportation-related applications. The study utilized a portable Wide Area Augmentation System (WAAS)-enabled GPS receiver which provides longitude and latitude data to an accuracy of 2 m, altitude data to an accuracy of 3 m, and speed measurements to an accuracy of 0.1 m/s. The GPS unit was designed to record date, time, vehicle longitude, vehicle latitude, vehicle speed, vehicle heading, and the number of tracking satellites.

The GPS floating-car travel data were collected using a test vehicle on weekdays (Monday through Friday) between March and May of 2006. The trip route (highway or arterial) was randomly selected on the day of data collection. To record the aggregate characteristics of traffic flow, the probe vehicle maintained the average speed of the traffic stream. The travel data were recorded at a 1-s resolution and downloaded to a personal computer. The minimum sample size (N) was calculated to satisfy the 95% confidence limits (Z value 1.96) using the standard deviation (σ) value and travel time error (δ) (see Eq. (1)). The GPS data that were gathered exceeded the required minimum sample size. In total, 39 valid trips were recorded, of which 21 traveled on the highway route and 18 traveled on the arterial route, while 10 trips on the highway route and 11 trips on the arterial route were required to satisfy the minimum sample size considering a 95% confidence limit.

$$N = \left(\frac{1.96}{\delta}\right)^2 \sigma^2 \tag{1}$$

While both morning and evening commute data were gathered, only morning commute data were used for the analysis. A MATLAB code was developed to extract the study section data from the entire morning commute travel data. The software automatically identified the first and last GPS points within the study corridor using the coordinates of the boundary study sections. Following the data reduction, a unique trip number was assigned to each trip.

4. Energy and emission models

To estimate emission and fuel consumption using the second-by-second GPS probe vehicle data, the VT-Micro model, the comprehensive modal emissions model (CMEM), and the Environmental Protection Agency's (EPA) MOBILE6 model were utilized. The following sections briefly describe each model and how the models were utilized in this study.

5. MOBILE6 model

The MOBILE6 model was developed by the EPA Office of Transportation and Air Quality. MOBILE6 is the latest of the MOBILE models. MOBILE6 was developed using recent vehicle-emission testing data collected by the EPA, CARB, and automobile manufacturers, as well as inspection and maintenance tests conducted in various states. Emission factors can be adjusted for different facility types and different average speeds based on vehicle testing over a series of facility cycles. Also, MOBILE6 estimates emission factors for the start portion and the running portion of the trip separately (EPA, 2002).

To model the highway trips, the average speed of each section (a highway section: VA 267 and I-495, and two arterial sections: VA 28 and VA 7) was individually simulated and combined later in the analysis. Since the study only demonstrates the relative energy and emission differences associated with motorists' route choices, only average speeds by facility type were utilized for the sensitivity analysis. Other input variables were assumed to be identical across both routes. Thus, default settings of vehicle model year, mileage rate, vehicle age, vehicle-type percentage, and altitude information were used in the models instead of the fleet characteristics of Northern Virginia. Furthermore, only exhaust running emissions of light duty gasoline vehicles (LDGV) without start emissions were considered in this study.

6. CMEM model

The CMEM Model was developed by researchers at the University of California, Riverside. CMEM estimates light-duty vehicle (LDV) and light-duty truck (LDT) emissions as a function of the vehicle's operating mode. The term "comprehensive" is utilized to reflect the ability of the model to predict emissions for a wide variety of LDVs and LDTs in various operating states. CMEM predicts second-by-second tailpipe emissions and fuel-consumption rates for a wide range of vehicle and technology categories. Vehicle operational variables (such as speed, acceleration, and road grade) and model-calibrated parameters (such as cold-start coefficients and engine-friction factor) are utilized as input data (Barth et al., 2000). To estimate fuel consumption and emissions, the CMEM vehicle categories 11 and 24 were utilized. Category 11 represents Tier 1 (relatively new, low-mileage vehicles) and category 24 represents Tier 1 (relatively old, high-mileage vehicles).

7. VT micro (ORNL) model

While the CMEM model was developed as a power-demand model, the VT-Micro model was developed as a regression model from experimentation with numerous polynomial combinations of speed and acceleration levels to construct a dual-regime model. The model was developed utilizing a number of data sources including data collected at the Oak Ridge National Laboratory (ORNL) (9 vehicles) and the EPA (101 vehicles). These data included fuel consumption and emission rate measurements (CO, HC, and NO_x) as a function of the vehicle's instantaneous speed and acceleration levels. CO_2 emissions were estimated using the carbon balance equation in conjunction with the fuel consumption measurements.

In this study, an average composite vehicle for the nine ORNL vehicles was utilized. This composite vehicle included six light-duty automobiles and three light duty trucks. These vehicles were selected to produce an average vehicle that was consistent with average vehicle sales in terms of engine displacement, vehicle curb weight, and vehicle type at the time the data were gathered. The VT-Micro model fuel consumption and emission rates were found to be highly accurate compared to the ORNL data with coefficients of determination ranging from 0.92 to 0.99. A more detailed description of the model derivation is provided in the literature (Ahn et al., 2004; Ahn et al., 2002; Rakha et al., 2004).

8. Field data analysis

8.1. Morning peak GPS data study

The average travel time results of the collected GPS data demonstrate that highway trips result in travel time savings of 17% with a smaller travel time variability compared to arterial trips (travel time standard deviation of 4.17 versus 5.08 min, respectively) – Table 1. To confirm the results, t-tests were performed at a 5% significance level assuming identical mean travel times for both cases. The t-test produced a p-value of 0.003, which indicates that there is sufficient evidence to reject the null hypothesis of equal travel times. Thus, we conclude that the travel times of the highway trips are significantly shorter than the travel times of the arterial trips even though the highway trips are 30% longer than the arterial trips (35.9 km versus 27.6 km). Table 1 also demonstrates that the highway trips have a significantly higher average speed than the arterial trips.

Fig. 2 shows the fuel consumption and emission rates estimated by the VT-Micro (ORNL), MOBILE6, and CMEM models for the highway and arterial trips. The figure demonstrates that a 47% reduction in HC emissions is achievable if motorists use the arterial route instead of the highway route based on the VT-Micro (ORNL) model estimates. Similarly, the output of the CMEM model demonstrates that the arterial trips result

Table 1
Trip characteristics of GPS data

	Highway	Arterial	Difference
Average travel time (min)	25.63	29.9	−4.27
95 Percentile of travel time	36.25	37.86	
5 Percentile of Travel time	23.32	26.23	
Standard deviation of travel time	4.17	5.08	−0.91
Average speed (km/h)	85.42	56.62	28.8
Standard deviation of speed	10.23	7.91	2.32
95 Percentile of speed	94.16	63.11	
5 Percentile of speed	59.26	43.94	
Distance (km)	35.9	27.6	8.3
Number of trips	21	18	

in savings in the range of 47–63% in HC emissions compared to the highway trips. Alternatively, the MOBILE6 model results demonstrate that highway trips reduce HC emissions by 36%.

Fig. 2 also illustrates the route choice impacts on other Measures of Effectiveness MOEs, including CO, NO_x, CO_2, and fuel consumption. Specifically, reductions in CO emissions in the range of 52%, 71%, and 64% were observed when motorists utilized the arterial based on the VT-Micro (ORNL vehicle), CMEM 11, and CMEM 24 models, respectively. The figure also shows that the use of the arterial route can produce reductions in NO_x and CO_2 emissions up to 45% and 20%, respectively. Some 18–23% of energy cost can be saved when motorists sacrifice 4.3 min of travel time in this case study. However, similar to the results of HC emissions, the MOBILE6 model estimated that CO and NO_x emissions were increased 7% and 23% when drivers selected the arterial route. The CO_2 and fuel consumption values of MOBILE6 are not presented in Fig. 2 because MOBILE6 only estimates HC, CO, and NO_x emissions. Also the absolute values of fuel consumption and emissions are not necessarily equal given the potential for different model characteristics; however, the intent of this paper is not to derive definitive emission inventories but to demonstrate the relative energy and emission differences associated with motorists' route choices. Indeed, since each emission model is based on a different dataset, each model generates different fuel consumption and emission values.

Two microscopic emission models and the MOBILE6 model produce different results for the same analysis. Specifically, VT-Micro and CMEM models predict that drivers can reduce energy consumption and emissions when they choose the arterial route while the MOBILE6 model estimates that the highway route is the better option that can achieve air quality improvement as well as travel time savings. The different results are attributed to the characteristics of emission models. Microscopic emission models such as VT-Micro and CMEM models estimate emissions and fuel consumption rates based on instantaneous vehicle engine loads, while the MOBILE6 model, which is a macroscopic emission model, predicts emissions based on the aggregate characteristics such as an average speed of a corridor. Thus it is reasonable to assert that the results from VT-Micro and CMEM models are more reliable to the estimated values in comparison to the MOBILE6 results because MOBILE6 is unable to capture the impact of instantaneous speed and acceleration levels on the various MOEs. These results clearly demonstrate the need to utilize microscopic energy and emission tools for the environmental assessment of alternative traffic operational projects.

The variations in HC emissions over the individual trips with travel time and average speed data for both highway and arterial trips are illustrated in Fig. 3. The figure illustrates that the trend of HC emissions from VT-Micro (ORNL vehicle) models is consistent with that of the CMEM models because both models are designed to capture the second-by-second operational behavior. Alternatively, the HC emissions of the MOBILE6 model were found to be more sensitive to the average speed of each trip than to the intricate differences in speed profiles. Because the CMEM, VT-Micro, and MOBILE6 models were developed based on different emission sources, the absolute values of each emission model are different. However, the general trends are consistent for the micro models but inconsistent in the case of the MOBILE6 model.

In addition, correlation coefficients among travel time, average speed, fuel consumption, and HC emissions of individual trips are shown in Table 2. The table shows that it is difficult to find relationships between travel time (or average speed) and the estimated emissions and fuel consumption rates produced by the VT-Micro (ORNL) and CMEM models considering the non-linear behavior of vehicle emissions, demonstrating that

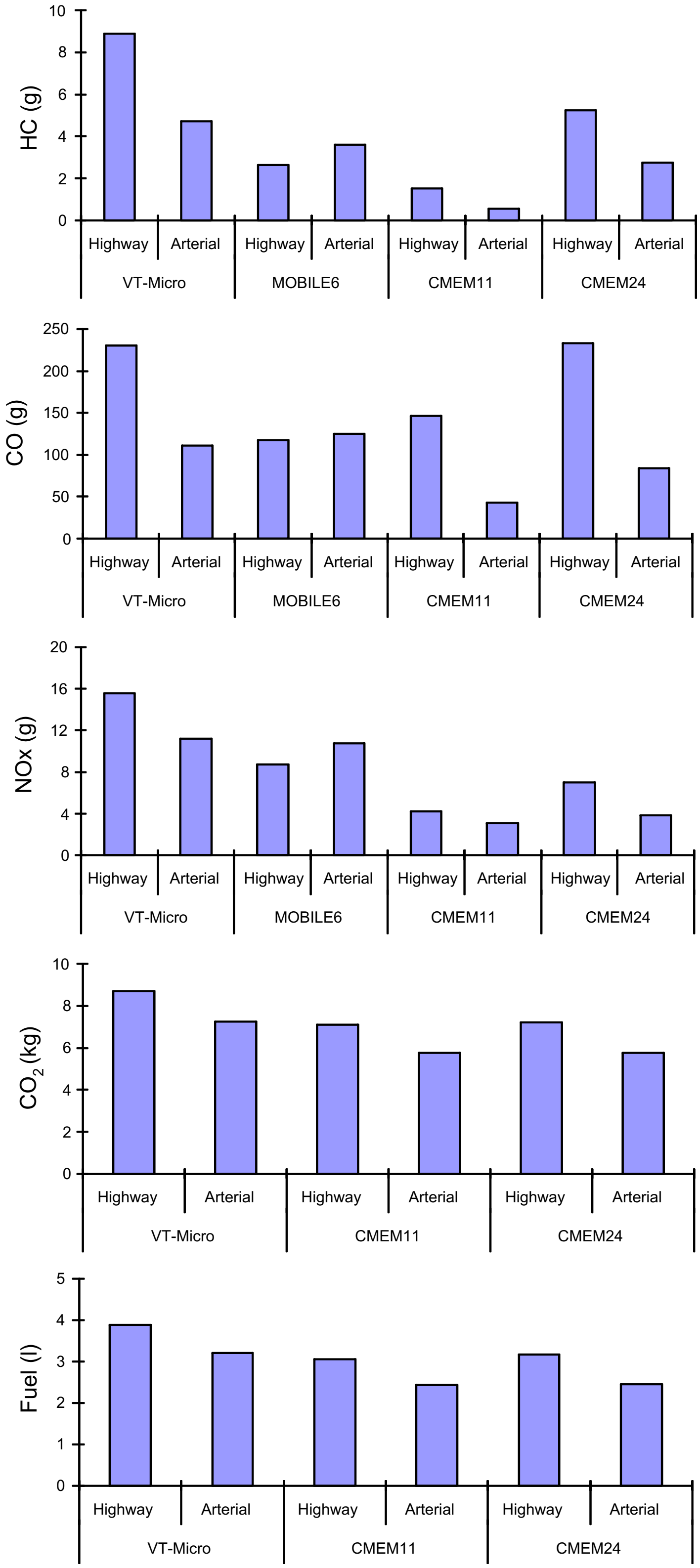


Fig. 2. Estimated emissions and fuel consumptions on study corridors.

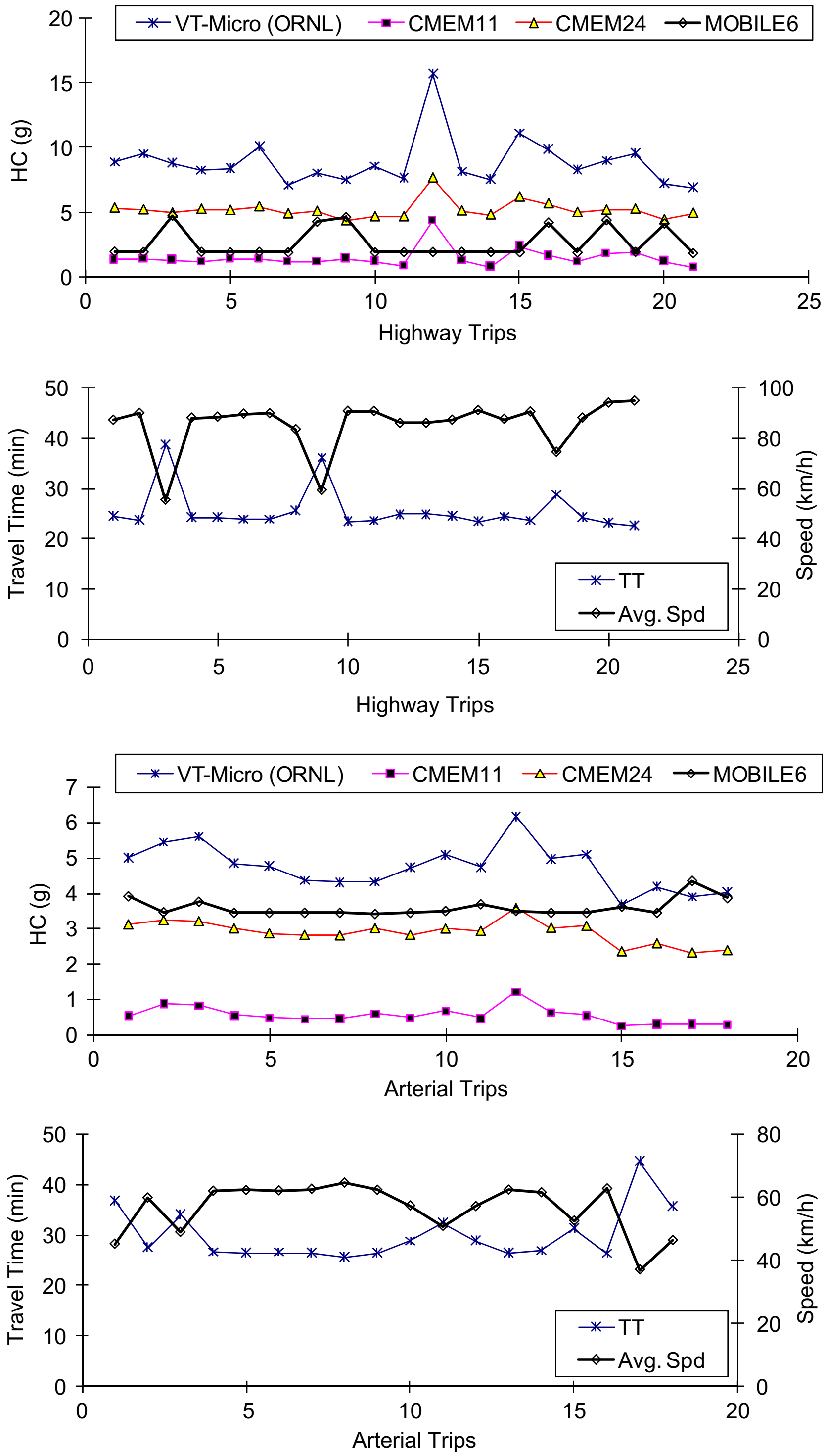


Fig. 3. HC emissions, travel times, and average speed of each trip.

MOEs produced by microscopic emission models are closely related to instantaneous vehicle operations as opposed to aggregate trip characteristics. However, high correlation coefficients are observed between travel time and HC emissions produced by MOBILE6, as demonstrated in Table 2. Also, the emissions and fuel con-

Table 2
Correlation coefficients between MOEs

	Highway trips				Arterial trips			
	ORNL	CMEM11	CMEM24	MOBILE6	ORNL	CMEM11	CMEM24	MOBILE6
Correlated with travel time	−0.06	0.02	−0.19	0.73	−0.21	−0.23	−0.52	1.00
Correlated with average speed	0.02	−0.06	0.15	−0.73	0.16	0.19	0.52	−0.98
Correlated with VT-Micro(ORNL)		0.94	0.94	−0.15		0.93	0.40	−0.24
Correlated with CMEM11 model			0.90	−0.03			0.51	−0.26
Correlated with CMEM24 model				−0.25				−0.53

sumption rates of the VT-Micro (ORNL vehicle) model are highly correlated with the results of the CMEM model due to the microscopic nature of the models.

8.2. Same travel time case study

Under congested conditions, motorists tend to choose the route with the minimum travel cost (e.g., travel time). Between each origin and destination, UE is reached when no driver can unilaterally achieve a reduction in time or cost by changing his/her route of travel; in other words, the travel times for all routes are equal. Fig. 4 presents the emissions and fuel consumption rates produced by the VT-Micro (ORNL vehicle), CMEM, and MOBILE6 models when the travel times of the highway trip and the arterial trip are identical. It may not be appropriate to claim that the UE condition is reached even under these conditions because the two trips were recorded on two different days. Fig. 4 illustrates that even when the travel times are identical, motorists can save significant emission and fuel consumption rates when the arterial route is selected. Specifically, the VT-Micro model estimates reductions in the range of 44%, 49%, 25% and 18% for HC, CO, NO_x, and CO_2 emissions, respectively. Furthermore, a driver can save up to 19% in fuel costs by using the arterial route.

Second-by-second emissions and fuel consumption of highway and arterial trips under UE conditions are illustrated in Fig. 5. The figure also includes the speed profiles of the highway and arterial trips, which involve several full and partial stops in addition to high-speed travel (speeds of about 100 km/h for the arterial trip and 120 km/h for the highway trip). The average speeds of the highway and arterial trips were 74 km/h and 57 km/h, respectively. Fig. 5 illustrates the variations in the instantaneous vehicle emissions and fuel consumption rates as estimated by the VT-Micro (ORNL vehicle) and CMEM 24 models as the vehicle traveled along the highway and arterial routes. The instantaneous emissions show the numerous peaks and valleys of the vehicle emissions, demonstrating that the MOEs are sensitive to changes in a vehicle's speed and acceleration profile. Also, some peaks of HC and CO emissions represent a significant amount of emissions. For example, a few peaks of CO emissions are several thousand times greater than those of other instantaneous emission rates.

Table 3 shows that 1% (17 s of 1729 s) of the highway trip is responsible for 16%, 19%, 3%, and 4% of the HC, CO, NO_x, CO_2 emissions, respectively, along the drive cycle shown in Fig. 5 when the MOEs are estimated by the VT-Micro (ORNL) model. The CMEM 24 model provides similar results. The results of the CMEM 24 model show that almost 100% of HC and NO_x emissions are emitted by 10% (173 s of 1729 s) of the arterial trip, implying that a small fraction of the trip is responsible for a significant amount of the emissions while the results of the VT-Micro show smaller contributions. In general, CO_2 emission and fuel consumption rates are impacted less than other MOEs; up to 25% and 28% of CO_2 emissions and fuel consumption rates are caused by 10% of the trip profile. These small portions of a trip produce high engine-load conditions. Consequently, the study demonstrates that a reduction of high-emitting driving behavior can significantly improve air quality.

9. Simulation results

9.1. Sensitivity analysis for various assignment scenarios

To examine the system-wide impacts of traffic assignment on air quality and energy, the study utilized the INTEGRATION microscopic traffic assignment and simulation software to conduct further analyses. The

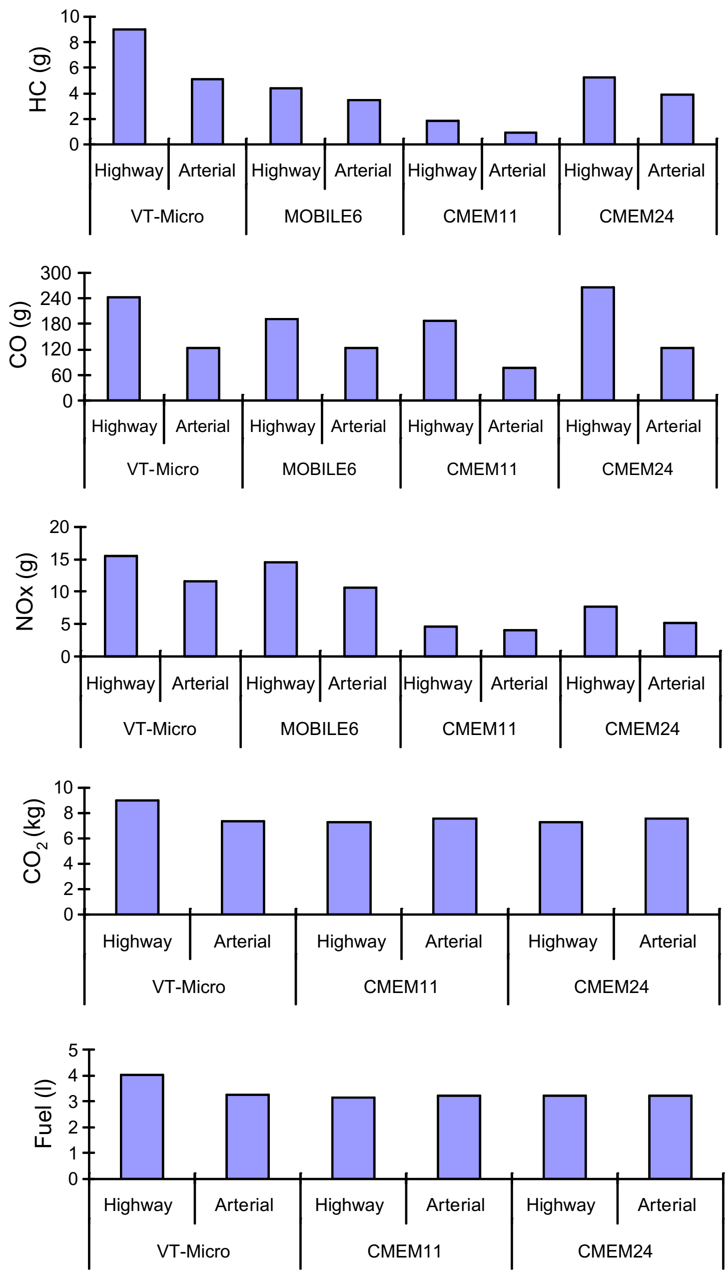


Fig. 4. Emissions and fuel consumption with same travel time.

INTEGRATION software utilizes VT-Micro fuel consumption and emission models with various vehicle types. A detailed description of the energy and emission modules within the INTEGRATION model is provided in the literature (Rakha and Ahn, 2004).

The sample network consists of two links and two nodes, as illustrated in Fig. 6. The O-D (origin-destination) demand is 5000 vehicles per hour (veh/h), and there are two routes available. The highway route is 5 km long with three lanes for the first 4 km and two lanes for the remaining 1 km. It has a free-flow speed of 100 km/h and a capacity of 1,800 veh/h/lane. The jam density of the highway route is set to 100 veh/km, and the speed-at-capacity is coded at 90 km/h. The arterial route is a shorter two-lane, 4 km corridor that has three signalized intersections located every 1 km, as illustrated in Fig. 6. The arterial route has a lower

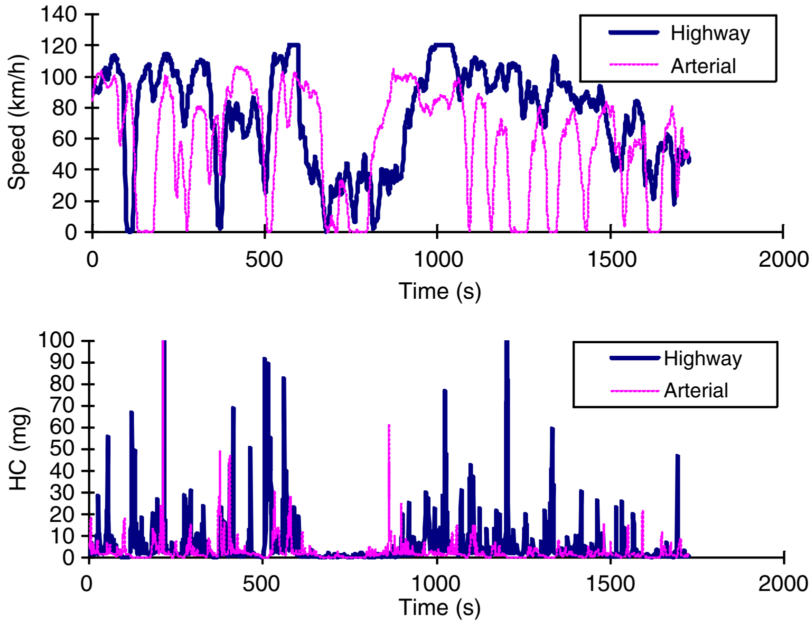


Fig. 5. Instantaneous HC emissions with same travel time.

Table 3
Emission percent that contributed to MOEs

	HC (%)	CO (%)	NO_x (%)	CO_2 (%)	Fuel (%)
ORNL highway					
Top 1	16	19	4	3	4
Top 2	24	30	7	6	7
Top 5	39	47	17	13	14
Top 10	54	64	32	23	25
ORNL arterial					
Top 1	15	20	5	3	4
Top 2	21	29	9	6	7
Top 5	34	45	21	13	14
Top 10	47	60	37	24	25
CMEM24 highway					
Top 1	20	38	30	3	5
Top 2	32	63	50	6	9
Top 5	52	80	73	14	17
Top 10	81	84	90	25	28
CMEM24 arterial					
Top 1	31	63	55	4	5
Top 2	47	66	64	7	8
Top 5	90	71	89	15	16
Top 10	100	77	100	26	27

free-flow speed of 75 km/h with a 67 km/h speed-at-capacity and an identical jam density and lane capacity as those for the highway route. Also, three signals have a 60 s cycle length with a 0.67 g/C ratio (effective green time to cycle length ratio), and they are partially coordinated.

Eleven traffic assignment scenarios were utilized in this case study. Fig. 7 shows the traffic assignment scenarios simulated using the INTEGRATION software. The vehicles assigned to the arterial route were

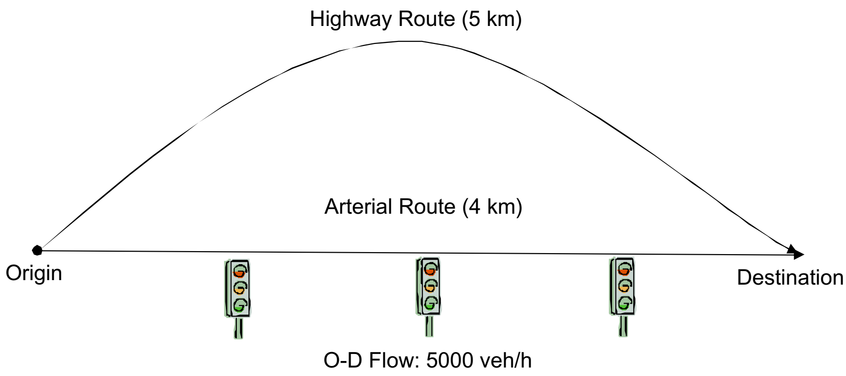


Fig. 6. Sample network utilized for simulation study.

increased from 500 vehicles (scenario 2) to 4500 vehicles (scenario 10) in increments of 500 vehicles; for example, scenario 5 shows that 2000 vehicles were assigned to the arterial route and 3000 vehicles were assigned to the highway route. Scenarios 1 and 11 were excluded from the rule; in other words, 100 vehicles and 4900 vehicles were assigned to the arterial route and the highway route, respectively, in scenario 1 and vice versa for scenario 11. Each simulation was loaded for 30 min and continued simulation for 90 min to clear all loaded vehicles. Therefore, 2500 vehicles were utilized for this analysis.

The simulation results show that the SO condition is attained in scenario 5, as illustrated in Fig. 7, which has the shortest travel time of the entire network. Fig. 7 also shows the UE condition in scenario 4, which has the same average travel time for the two routes. Also, it is demonstrated that the travel times (or delay) are significantly increased as 4000 veh/h or more are assigned to the arterial route due to the over-saturated delay.

The emissions- and/or fuel-consumption-optimized traffic assignments are illustrated in Fig. 8. Scenario 8 demonstrates the HC and CO emission-optimized traffic assignment while scenario 5, which represents the SO condition based on travel time, also produces the minimum CO_2 emission and fuel consumption rates. These results are inconsistent with the results of Rilett and Benedek (1994), in which the traffic flows of the CO-optimized assignment condition were roughly equivalent to the flows of the UE and SO conditions within a small error range. Also, scenario 11, which assigns most of the vehicles to the arterial route and has the greatest delay among all scenarios (8.4 times more delay than SO condition), produces the least NO_x emissions. It is caused by the fact that low-speed congested traffic conditions, which are typically under fuel-rich or fuel-lean conditions, do not increase NO_x emission while more NO_x emissions are produced under stoichiometric air/fuel ratio conditions.

Furthermore, HC and CO emissions, NO_x emissions, CO_2 emissions, and fuel consumption rates have different emission- and/or energy-optimized assignments, which are scenarios 8, 11, and 5, respectively. This is attributed to the fact that each emission group has different characteristics; HC and CO emissions are extremely sensitive to vehicle acceleration behavior, and the highest emissions are produced under fuel-rich conditions while more NO_x emissions are generated under a stoichiometric ratio condition. Fuel consumption and CO_2 emissions are also sensitive to acceleration behaviors but not as sensitive as HC and CO emissions.

9.2. Sensitivity analysis using various vehicle types

Fig. 9 illustrates emission- and energy-optimized traffic assignments for high-emitting (HE4) and low-emitting (LDV3) vehicles as well as the ORNL vehicles. High-emitting vehicles (or High emitters) are motor vehicles that produce higher emissions than the average-emitting vehicle under normal driving conditions. It is known that a small fraction of high emitters contributes significantly to mobile source emissions. Detailed descriptions of high-emitting (HE4) and low-emitting (LDV3) vehicles are provided in the literature (Ahn et al., 2004; Rakha et al., 2004), and both emission models were incorporated into the INTEGRATION software. The figure clearly illustrates that high-emitting vehicles emit significantly higher HC, CO, and NO_x emissions compared to other vehicle types, and low-emitting vehicles produce lower emissions when compared to

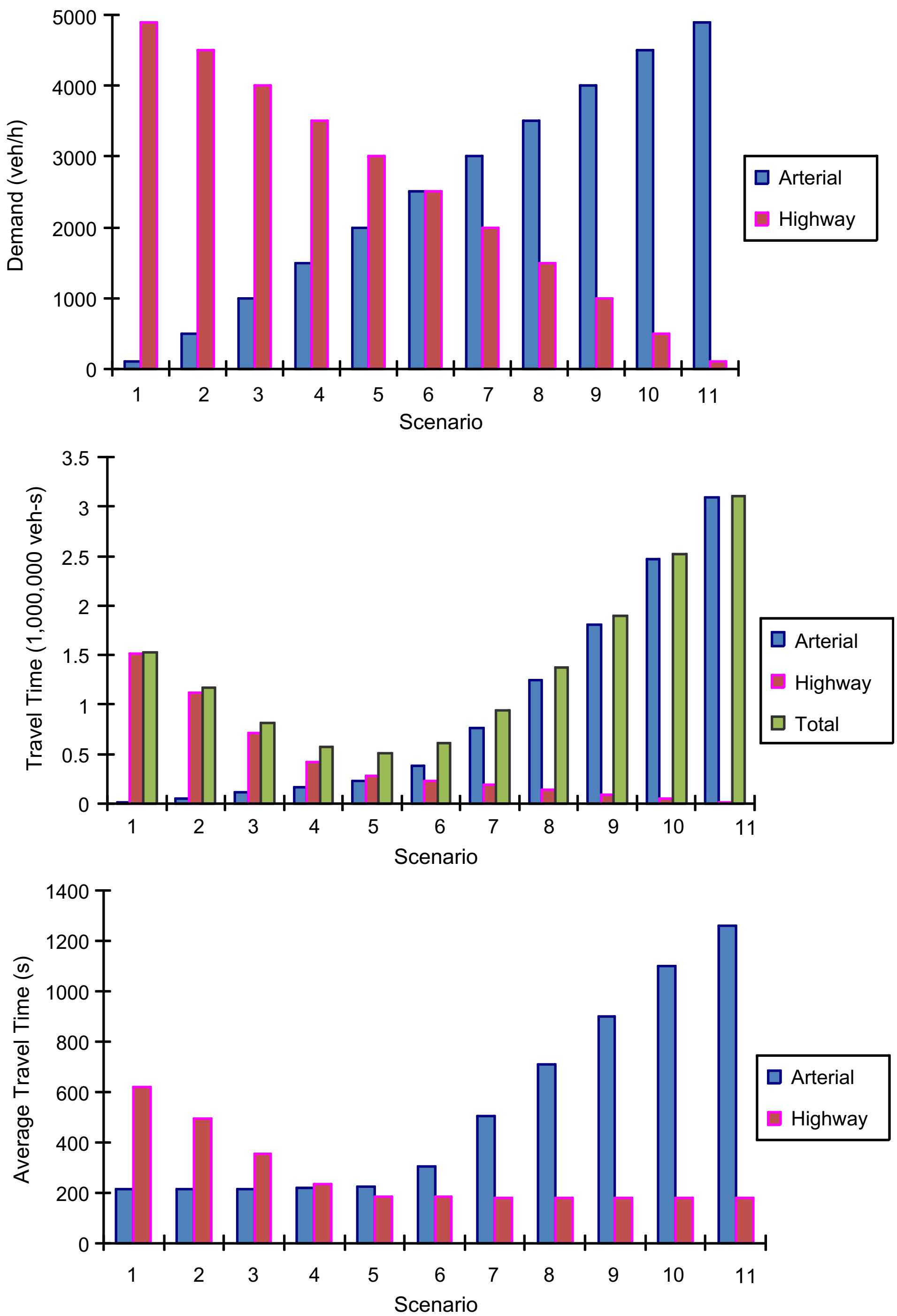


Fig. 7. Simulation scenario and results.

the ORNL composite vehicle. Also, the figure shows that the ORNL vehicles consume more fuel than high emitters. High-emitting vehicles typically emit more emissions but do not consume more fuel than normal vehicles. Since the engine sizes of the ORNL vehicles are larger than that of the high emitting vehicle, they consume more fuel.

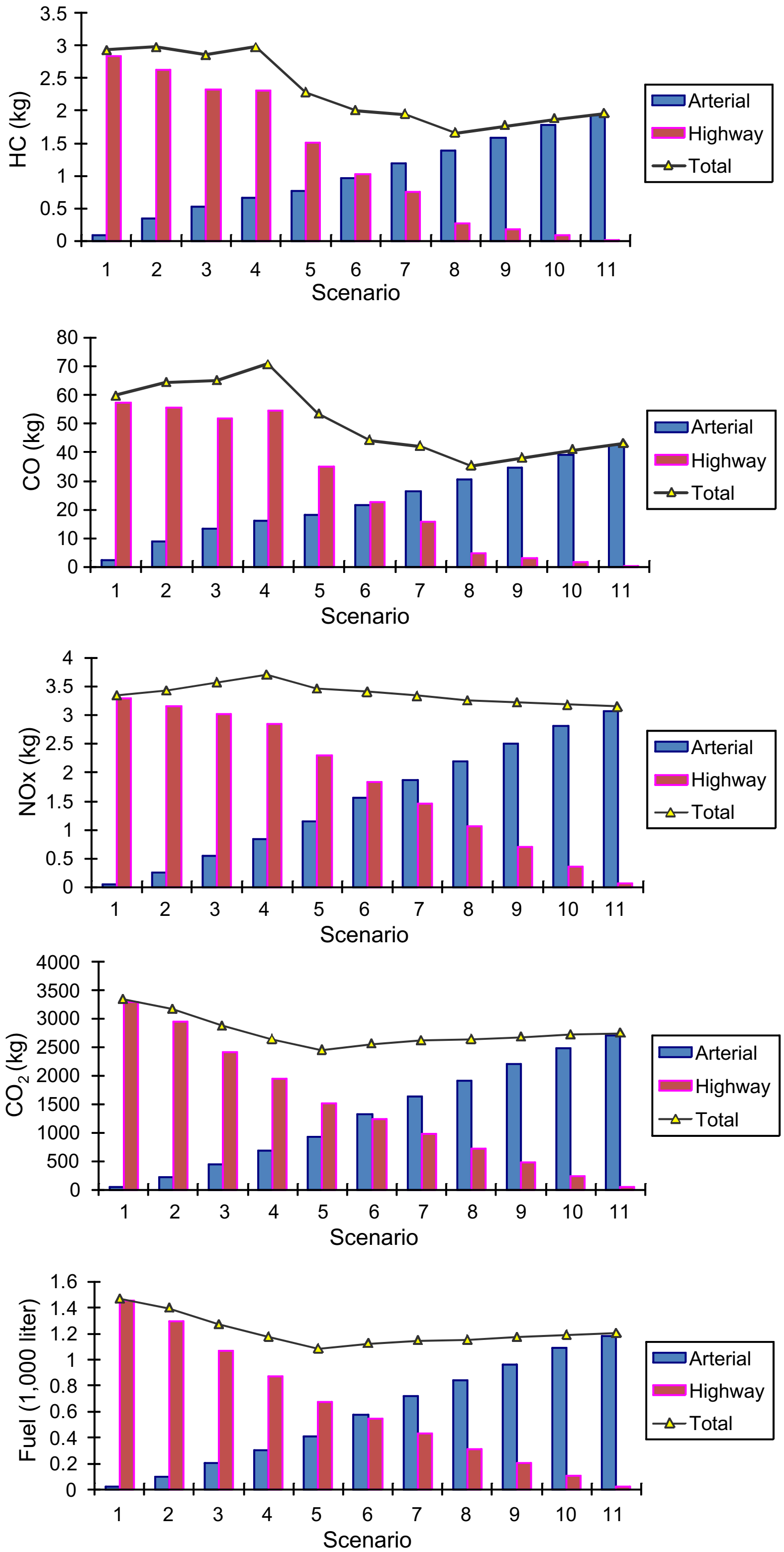
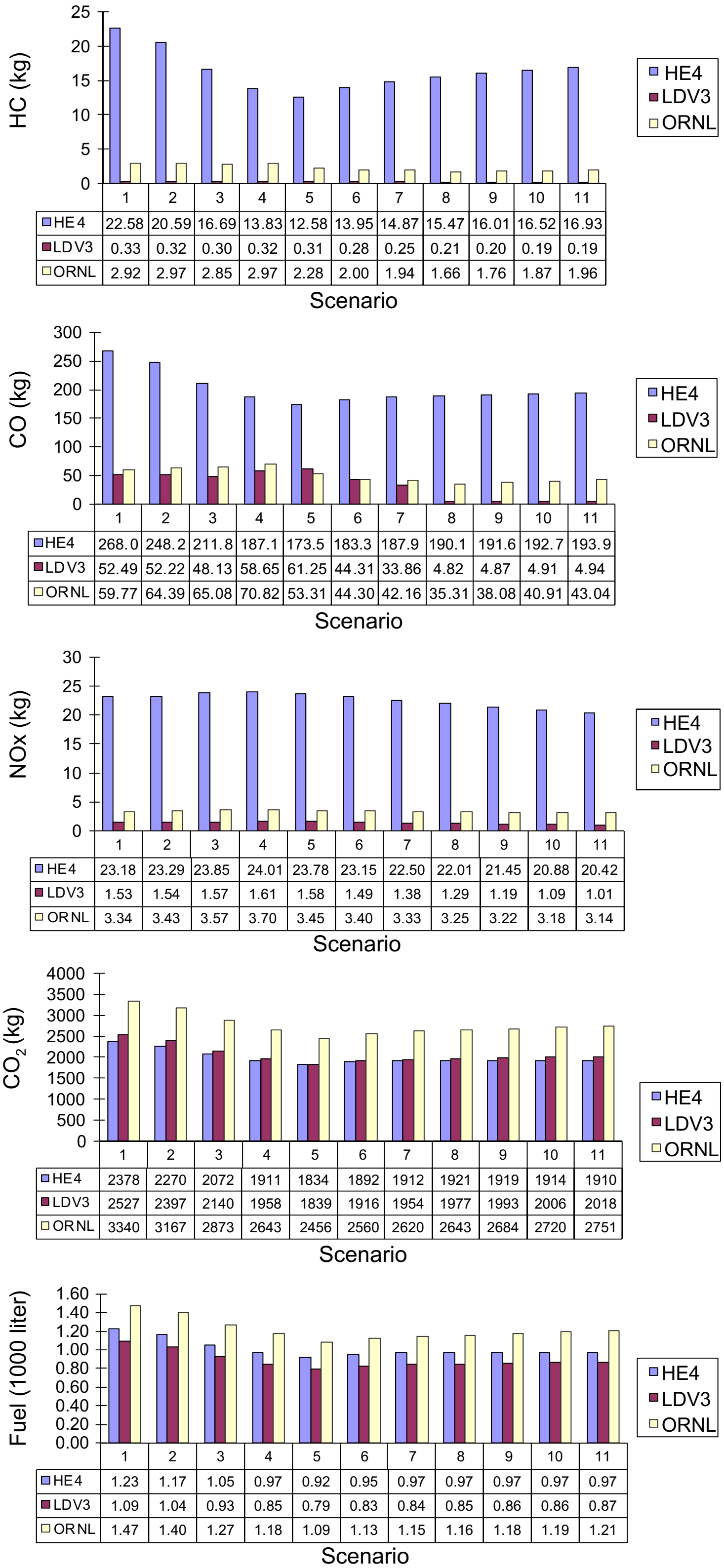


Fig. 8. Fuel consumption and emissions of various O-D demands.



HC (kg)	1	2	3	4	5	6	7	8	9	10	11
HE4	22.58	20.59	16.69	13.83	12.58	13.95	14.87	15.47	16.01	16.52	16.93
LDV3	0.33	0.32	0.30	0.32	0.31	0.28	0.25	0.21	0.20	0.19	0.19
ORNL	2.92	2.97	2.85	2.97	2.28	2.00	1.94	1.66	1.76	1.87	1.96

CO (kg)	1	2	3	4	5	6	7	8	9	10	11
HE4	268.0	248.2	211.8	187.1	173.5	183.3	187.9	190.1	191.6	192.7	193.9
LDV3	52.49	52.22	48.13	58.65	61.25	44.31	33.86	4.82	4.87	4.91	4.94
ORNL	59.77	64.39	65.08	70.82	53.31	44.30	42.16	35.31	38.08	40.91	43.04

NOx (kg)	1	2	3	4	5	6	7	8	9	10	11
HE4	23.18	23.29	23.85	24.01	23.78	23.15	22.50	22.01	21.45	20.88	20.42
LDV3	1.53	1.54	1.57	1.61	1.58	1.49	1.38	1.29	1.19	1.09	1.01
ORNL	3.34	3.43	3.57	3.70	3.45	3.40	3.33	3.25	3.22	3.18	3.14

CO_2 (kg)	1	2	3	4	5	6	7	8	9	10	11
HE4	2378	2270	2072	1911	1834	1892	1912	1921	1919	1914	1910
LDV3	2527	2397	2140	1958	1839	1916	1954	1977	1993	2006	2018
ORNL	3340	3167	2873	2643	2456	2560	2620	2643	2684	2720	2751

Fuel (1000 liter)	1	2	3	4	5	6	7	8	9	10	11
HE4	1.23	1.17	1.05	0.97	0.92	0.95	0.97	0.97	0.97	0.97	0.97
LDV3	1.09	1.04	0.93	0.85	0.79	0.83	0.84	0.85	0.86	0.86	0.87
ORNL	1.47	1.40	1.27	1.18	1.09	1.13	1.15	1.16	1.18	1.19	1.21

Fig. 9. Fuel consumption and emissions of various vehicle types.

Table 4
Benefit of using emission optimized traffic assignment

	HC (%)	CO (%)	NO_x (%)	CO_2 (%)	Fuel (%)
ORNL vehicles					
Saving over UE condition	44.32	50.15	15.11	7.09	7.76
Saving over SO condition	27.26	33.77	8.96	0.00	0.00
HE4 vehicles					
Saving over UE condition	9.03	7.25	14.95	4.04	4.61
Saving over SO condition	0.00	0.00	14.12	0.00	0.00
LDV3 vehicles					
Saving over UE condition	39.89	91.78	37.44	6.09	6.30
Saving over SO condition	38.87	92.13	36.40	0.00	0.00

Fig. 9 illustrates that fuel consumption and CO_2 emissions have the same optimized assignment, scenario 5, for all vehicle types. Similarly, minimum NO_x emissions for all vehicle types are observed in scenario 11. However, HC and CO emissions have different emission-optimized assignments for each vehicle type. Fig. 9 shows that the emission-optimized assignment of HC and CO emissions for high-emitting vehicles is scenario 5, which is the SO condition, while in terms of low-emitting vehicles, lower HC and CO emissions are observed as more traffic is assigned to the arterial route. This trend is caused by the fact that high-emitting vehicles typically generate more emissions at low speeds and acceleration-operational conditions than normal vehicles due to various reasons (e.g., malfunction of catalytic converter) while low-emitting vehicles produce significantly lower emissions under the same operational conditions. Catalytic converters typically operate better under low speed and acceleration-operational conditions than they do under high-speed operational conditions. Thus, low-emitting vehicles produce small amounts of HC and CO emissions when they are assigned to the low-speed arterial route. Therefore, it is recommended that to reduce HC and CO emissions, more low-emitting vehicles should be assigned to lower-speed routes. However, from a societal standpoint this may not be an efficient approach, given that such an assignment would be providing better routes to environmentally less-efficient vehicles and thus would encourage drivers not to fix their vehicles.

Table 4 demonstrates that vehicle emission and fuel consumption rates can be reduced when emission- and energy-optimized assignments are utilized. As seen in the table, the emission-optimized assignments provide a significant reduction in emissions, particularly of HC, CO, and NO_x. However, the savings of CO_2 emission and fuel consumption rates of emission-optimized assignment over UE assignment are less than HC, CO, and NO_x emissions but are still in the range of 4.0–7.6%. The emission-optimized assignments produce significant emission reductions over the UE and SO assignments. The table shows that low-emitting vehicles can save more HC, CO, and NO_x emissions (38.87%, 92.13%, and 36.40%, respectively) when the emission-optimized assignment is utilized than can other vehicle types over the SO and UE assignment because low-emitting vehicles have significantly different traffic flows compared to SO and UE conditions. Also, relatively smaller HC, CO, and NO_x emission reductions are found for high emitters.

10. Conclusions

The environmental and energy impacts of route choice behavior were investigated using second-by-second GPS commute data and a micro-simulation study. The results provide convincing evidence that a UE and SO traffic assignment does not necessarily minimize vehicle fuel consumption and emissions based on the second-by-second GPS commute field data and the simulation results. For the specific example illustration, while motorists could save additional travel time on highway travel over travel on an arterial route, significant improvements to air quality and energy savings were observed when motorists utilized the longer time arterial route. In addition, different emission- and/or energy-optimized assignments should be recommended for each pollution type and fuel consumption; in other words, each vehicle type has different HC and CO emission-optimized assignment conditions and minimum NO_x emissions are achieved when most of the vehicles are assigned to the low-speed arterial route while CO_2 emission- and energy-optimized assignment is identical to the SO assignment. Furthermore, the composition of various vehicle types should be cautiously examined before implementing emission- and energy-optimized assignments. Since high-emitting vehicles typically generate more emissions at low speed and acceleration-operational conditions than normal vehicles, while low-emitting vehicles produce significantly low emissions under the same operational conditions, it is recommended that to reduce HC and CO emissions, more low-emitting vehicles should be assigned to lower-speed routes. The study also found that the emission-optimized assignments produce significant emission reductions, up to 92% of CO emission, over the UE and SO assignments. It was found that a small portion of the entire trip that involves operation at high engine loads is responsible for a significant amount of trip emissions and fuel consumption rates. The results suggest that significant improvements in air quality and energy consumption are achievable by educating drivers. Finally, the research effort demonstrates the deficiency of macroscopic environmental tools (e.g., MOBILE6) in evaluating the environmental impacts of traffic operational projects.

References

Ahn, K., Rakha, H., Trani, A., 2004. Microframework for modeling of high-emitting vehicles. Transportation Research Record 1880, 39–49.

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. Journal of Transportation Engineering 128, 182–190.

Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M., Wenzel, T., 2000. Comprehensive Modal Emission Model (CMEM), version 2.0 user's guide, Riverside.

Benedek, C.M., Rilett, L.R., 1998. Equitable traffic assignment with environmental cost functions. Journal of Transportation Engineering – ASCE 124, 16–22.

EPA. 2002. User's Guide to Mobile6, Mobile Source Emission Factor Model. EPA420-R-02-001, Ann Arbor, Michigan.

Nagurney, A., 2000. Congested urban transportation networks and emission paradoxes. Transportation Research, Part D: Transport and Environment 5, 145–151.

Nagurney, A., Dong, J., 2002. A multiclass, multicriteria traffic network equilibrium model with elastic demand. Sage Urban Studies Abstracts 304, 415–517.

Nagurney, A., Ramanujam, P., Dhanda, K.K., 1998. Multimodal traffic network equilibrium model with emission pollution permits: compliance vs noncompliance. Transportation Research, Part D: Transport and Environment 35, 349–374.

Rakha, H., Ahn, K., 2004. Integration modeling framework for estimating mobile source emissions. Journal of Transportation Engineering 1302, 183–193.

Rakha, H., Ahn, K., Trani, A., 2004. Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. Transportation Research, Part D: Transport and Environment 91, 49–74.

Rilett, L.R., Benedek, C.M., 1994. Traffic assignment under environmental and equity objectives. Transportation Research Record 1443, 92–99.

Schrank, D., Lomax, T., 2005. The 2005 Urban Mobility Report. Texas Transportation Institute, College Station.

Sugawara, S., Niemeier, D.A., 2002. PART 2 – AIR QUALITY – how much can vehicle emissions be reduced? Exploratory analysis of an upper boundary using an emissions-optimized trip assignment. Transportation Research Record 1815, 9.

Tzeng, G.H., Chen, C.H., 1993. Multiobjective decision-making for traffic assignment. IEEE Transactions on Engineering Management 40, 180–187.