New Technique for Evaluating Urban Traffic Energy Consumption and Emissions

Edward B. Lieberman, KLD Associates, Inc.
Stephen Cohen, Federal Highway Administration

This paper describes the development of a computerized tool designed to provide accurate, location-specific estimates of fuel consumption and vehicle emissions, stratified by vehicle type. This tool is an extension of the UTCS-1 microscopic traffic simulation program developed previously for the Federal Highway Administration. Data bases representing fuel consumption and emission rates are provided by other models developed for the Transportation Systems Center and the Environmental Protection Agency respectively. These data bases and the models that produced them are described. Results obtained by applying the extended UTCS-1 model to networks representing a portion of the CBD in Washington, D.C., are presented. First, the effects of allowing right turns on red on traffic operations and on fuel consumption and vehicle emissions are assessed. Then a comparison is made of two signal timing patterns. These results indicate that right turns on red can improve fuel consumption by approximately 4 percent and reduce emissions by 6 percent. Improving signal timing patterns for the cases studied can produce a 25 percent improvement in fuel consumption and vehicle emissions.

Traffic engineers concerned with improving traffic operations in urban areas generally base their evaluation on measures such as accident reduction, volume, vehicle delay, vehicle stops, and mean speed. Environmental engineers have conducted impact studies addressing the effect of vehicle emissions by basing their calculations on average vehicle speeds and volume.

Recent events have provided the impetus for traffic engineers to consider energy consumption and vehicle emissions in their assessments of traffic operations. Similarly, environmentalists must become more familiar with the details of traffic operations to improve the precision of vehicle emissions estimates. While some recent studies have reflected the need for synthesizing traffic operations and environmental considerations, the use of simplifying assumptions, which can compromise results, is still a prevalent practice.

This paper describes the development of a computerized tool designed to provide accurate, location-specific estimates of fuel consumption and vehicle emissions, stratified by vehicle type—automobile, truck, bus. This tool is an extension of the UTCS-1 microscopic traffic simulation model developed for the Federal Highway Administration (5). Data bases representing fuel consumption and emission rates are provided by other models developed for the Transportation Systems Center (TSC) and the Environmental Protection Agency (EPA) respectively. Results obtained by applying this extended UTCS-1 model to a network representing a portion of the CBD in Washington, D.C., are presented. The effects of right turns on red (RTOR) and two signal timing patterns are assessed. A further comparison is made with results obtained by using values derived from average speed estimates.

BASIC CONSIDERATIONS

Vehicle fuel consumption rates and emission rates depend on many factors including vehicle type, size, and age; propulsion and transmission system; engine temperature; antipollution devices; optional features; and operating characteristics. During the last several years, research activities conducted for EPA and TSC have led to the development of two valuable models:

1. An automobile exhaust emission modal analysis model (1, 2) based on a voluminous data base (3) and
2. A computer program that simulates the performance of a vehicle engine to estimate fuel consumption rates (4).

Each of these models will provide a data base for specified vehicles of sufficient detail to construct a response surface of emission rates or fuel consumption rates in the speed-acceleration plane (Figure 1).

As described later, such response surfaces were derived for a representative (composite) automobile, truck, and bus. Figures 2 through 5 show curves representing sections through these response surfaces along lines of constant acceleration for the composite automobile. The units shown are those of the tables used to define the response surfaces. The following comments are based on examination of these curves.

1. The effect of vehicle acceleration on energy con-

Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

sumption rates and on all emission rates considered is most pronounced.

2. At a given acceleration, the rate of fuel consumption is relatively insensitive to speed over a broad range of speeds.

3. Deceleration causes an increase in emission rates of carbon monoxide (CO) and hydrocarbon (HC) pollutants relative to those at zero acceleration. Deceleration has a negligible effect on energy consumption and a beneficial one on emission of oxides of nitrogen (NO_x).

4. The rates of CO and HC emissions are insensitive to speed at zero acceleration; the sensitivity of emission rates increases with speed.

The data bases permit accurate determination of energy consumption and pollutant emissions for specified fleets of vehicles if their trajectories are known. As indicated, the resolution of these trajectories must be sufficiently microscopic to provide the necessary resolution of speed and acceleration, inasmuch as all measures are extremely sensitive to small differences in acceleration.

With these factors in mind, FHWA decided to extend the scope of the existing UTCS-1 traffic simulation program. UTCS-1 is a validated microscopic traffic simulation model in which each vehicle is identified and processed as a discrete entity. The program produces the necessary vehicle trajectories and provides values of speed and acceleration at 1-s time intervals. As many as 10 vehicle types may be identified. Buses and trucks are identified and processed as such. For full details, see Worrall and Lieberman (6).

In this paper, values are expressed in customary units to be compatible with model design.

DEVELOPMENT OF THE MODEL

The UTCS-1 traffic simulation model (5, 6) traces the trajectory of each vehicle traversing the network, with a resolution of 0.1 s. At the conclusion of each 1-s time step, the status of each vehicle is determined and all relevant data items are packed within a single vehicle-trajectory word. These items include

1. Location—network link and longitudinal position to ±8ft;
2. Vehicle type—automobile, truck, or bus;
3. Acceleration or deceleration—to nearest integer in feet per second squared; and
4. Speed—to nearest integer in feet per second.

The simulation model was refined and extended to produce, for each second of simulated time, a record of data on a peripheral device. This record consists of a vector of vehicle-trajectory words, each word representing one vehicle on the network. At the conclusion of a specified interval of simulated time (say, 15 min) a new module named FUEL is called by the UTCS-1 executive routine to process these records of trajectory words. A table look-up procedure locates the fuel consumed and emissions corresponding to the data included within each vehicle-trajectory word. The structure of UTCS-1 is shown in Figure 6.

For each vehicle type, the following measures of effectiveness are computed and printed, in addition to the traffic operations data:

1. Gallons of gasoline consumed,
2. Fuel consumption rate in miles per gallon, and
3. CO, HC, and NO_x emissions in grams per vehicle-mile.

This information is presented for each network link and is also aggregated over the network.

GENERATING THE DATA BASE

The TSC model (4) simulates the operation of a motor vehicle as it executes a speed-acceleration trajectory (also known as a driving schedule). This is accomplished by computing the load that is placed on the engine at every point on the trajectory. The model then computes the amount of fuel the engine must consume to output sufficient energy to overcome the loading requirement.

The load on the engine can be split into several parts:

1. The forces to be overcome at the rear wheels;
2. The rotational inertia at the rear wheels due to the rotating parts such as the wheel, universal components, and drive shaft;
3. Losses in the universal and the transmission gears;
4. Losses in the automatic transmission torque converter;
5. Accessory loads (i.e., air conditioning, fan, power steering); and
6. Rotational inertia of the front end rotating components (including the engine).

The forces to be overcome at the rear wheels consist of tire rolling resistance, aerodynamic drag, acceleration inertia, and grade climbing. In this application grade effects were ignored because the main contributor to fuel consumption in urban environments is stop-and-go driving caused by control devices.

The fuel requirements of the engine thus can be obtained from the engine map, which yields the brake-specific fuel consumption as a function of engine revolutions per minute and brake mean effective pressure.

Karl Hergenrother, who developed the TSC model, calibrated it for FHWA to generate tables of instantaneous fuel consumption rates related to vehicle speed and acceleration.

These data represent a weighted composite of 1971 vehicles based on 11 automobiles and 9 engines. This weighting reflects the proportion of each automobile class in the total automobile population. These classes of automobiles were selected to be consistent with the composite used to obtain the emissions data, discussed later. The TSC model was also calibrated to generate tables for a city diesel bus (with a two-speed automatic transmission) and a heavy gasoline-powered truck (with a five-speed manual transmission) commonly used in urban areas.

The tables of emission rates for this study were generated by using the results obtained from a program of dynamometer tests of 1020 passenger cars chosen at random in which HC, CO, and NO_x emissions were measured (3). All vehicles were tested over the surveillance driving schedule, which consists of five steady-state (constant speed) modes and 32 acceleration-deceleration modes. Here, a mode consists of a monotonic segment of a driving schedule. The 1020 vehicles were aggregated into 11 classes, depending on test conditions. An analytical study (1, 2) processed the emissions data for each mode and developed a regression relation. The regression relation had 12 coefficients and included some cubic and quartic terms in the product of acceleration and speed. A total of 33 regression expressions are available, one for each of three emittants and 11 classes of automobiles.

It was assumed that these regression relations were valid for the instantaneous emissions rates. In this study, the available 1971 group of vehicles was considered to be most representative of the present vehicle fleet. The associated regressions were used to generate three

Figure 1. Response surface of emission rates and fuel consumption rates in the speed-acceleration plane.

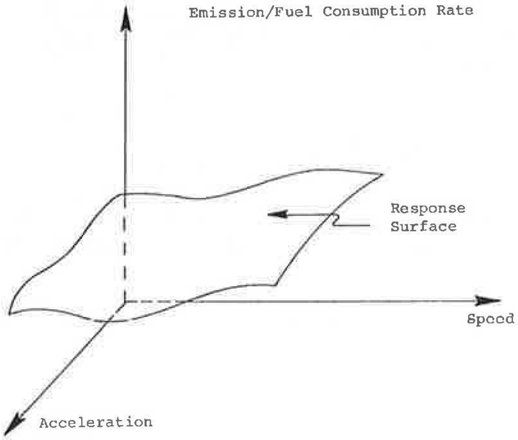


Figure 2. Automobile fuel consumption versus speed for several acceleration rates.

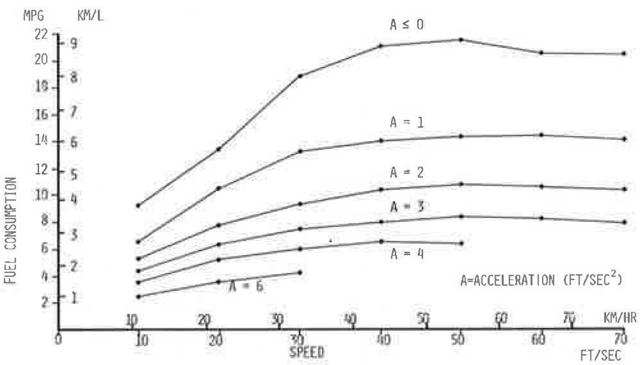


Figure 3. Automobile CO emissions versus speed for several acceleration rates.

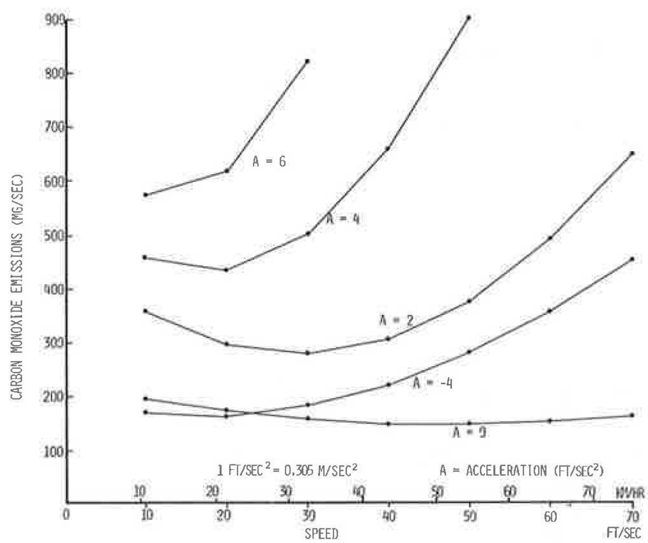


Figure 4. Automobile HC emissions versus speed for several acceleration rates.

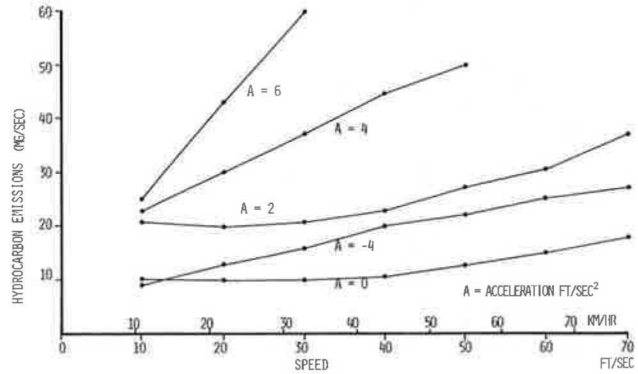


Figure 5. Automobile NO_x emissions versus speed for several acceleration rates.

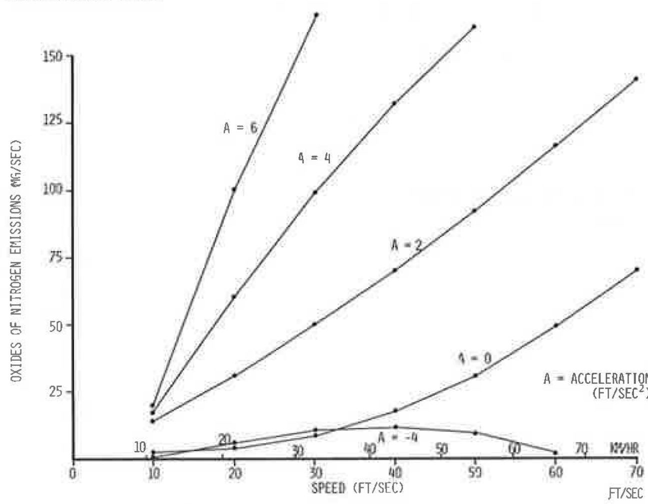
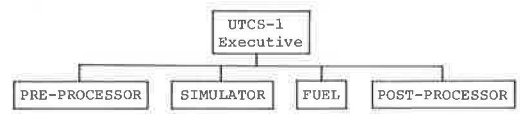


Figure 6. Structure of the UTCS-1 model.



PRE-PROCESSOR: Reads and stores all inputs, performs a wide range of diagnostic tests, and primes storage

SIMULATOR: Performs the microscopic simulation of urban traffic flow, aggregating and storing MOE statistics in the process

FUEL: Reads and processes the vehicle trajectory data and prints the fuel consumption and emission results

POST-PROCESSOR: Performs an evaluation by statistically comparing the results of two separate sets of MOE describing traffic operations (optional)

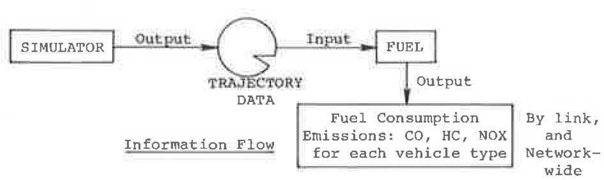
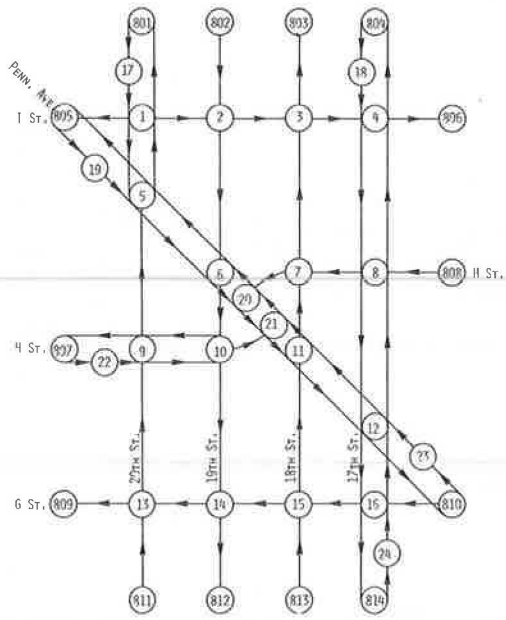


Figure 7. CBD network in Washington, D.C.



emissions tables over the same speed and acceleration ranges used for the fuel consumption data. Because of the cubic and quartic terms in the regression expressions, the tabulated values tended to oscillate rapidly and some values of emission rates were negative. When this occurred, the values were set to zero. The authors were unable to locate any emissions data of sufficient detail for trucks and buses.

The accuracy of these tables was tested by using them to compute the fuel consumption and emissions for the composite passenger car traversing the federal short cycle driving sequence (3, pp. 2-51). The results were as follows:

Item	Value
Fuel consumption, km/liter	7.14
HC, g/km	1.36
CO, g/km	19.0
NO_x, g/km	2.44

These results are within 2 percent of those experimentally devised values given in the literature (3).

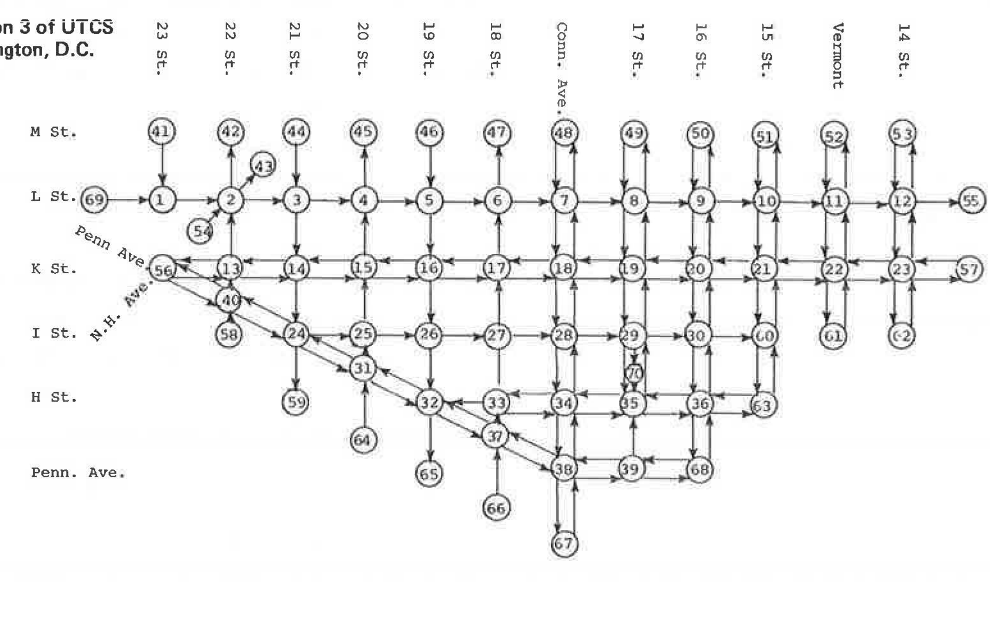
Table 1. Results of RTOR evaluation.

Control	Vehicle-km	Mean Speed (km/h)	Stops per Vehicle	Total Fuel (liters)	Gas Consumption (km/liter): From Model	Gas Consumption (km/liter): Based on Average Speed	Emissions (g/km): HC	Emissions (g/km): CO	Emissions (g/km): NO_x
No RTOR	1246	17.65	1.60	323.5	3.62	4.53	3.06	54.61	4.14
	1531	16.29	1.71	423.5	3.44	4.45	3.25	58.80	4.18
	1744	11.62	1.88	605.7	2.78	4.06	4.17	79.62	4.52
With RTOR	1247	18.91	1.53	312.1	3.76	5.50	2.91	51.27	4.07
	1529	17.72	1.62	402.8	3.61	4.59	3.06	54.65	4.11
	1759	13.47	1.73	558.4	3.02	4.08	3.77	70.44	4.41

Table 2. Results of signal timing evaluation on urban network.

Signal Timing	Vehicle-km	Mean Speed (km/h)	Stops per Vehicle	Total Fuel (liters)	Gas Consumption (km/liter)	Emissions (g/km): HC	Emissions (g/km): CO	Emissions (g/km): NO_x
SIGOP	3761	14.06	2.46	1175.2	3.22	3.62	66.2	4.24
TRANSYT	3616	17.86	1.92	952.3	3.78	3.03	52.9	4.02

Figure 8. Section 3 of UTCS network, Washington, D.C.



APPLICATIONS

The modified UTCS-1 model has been applied extensively since it was completed in mid-1974. Among the first applications was a study to explore the effects of the right-turn-on-red (RTOR) control feature on traffic operations, fuel consumption, and emissions over a range of traffic volumes. A portion of the CBD network in Washington, D.C., was studied with the model (Figure 7). The existing traffic volumes in the a.m. peak hour were studied, as was the impact of increasing or decreasing these volumes by 20 percent. The results of this study are given in Table 1.

It is instructive to compare the results for fuel consumption, obtained from the TSC data base by applying the value of mean speed at zero acceleration, and the data generated by the model. As indicated in Table 1, basing estimates of fuel consumption on a measure of average speed leads to an optimistic view of fuel consumption, by as much as 46 percent. This error reflects the sensitivity of fuel consumption to acceleration, as noted earlier. Hence, using only an (accurate) estimate of average speed ignores the turbulent characteristic of urban traffic flow, which contributes so strongly to fuel consumption. All of these comments apply equally to determining vehicle emissions.

Another study was designed to assess the relative impact of two signal timing patterns, generated with different algorithms (7, 8). The results generated by the model are given in Table 2 for the study network shown in Figure 8.

Examination of Tables 1 and 2 reveals that the RTOR provision can provide approximately a 4 percent reduction in fuel consumption and 6 percent reduction in vehicle emissions. An improved signal timing pattern can yield substantially greater benefits. In the study conducted, these benefits, expressed as reductions in fuel consumption and vehicle emissions, can range as high as 25 percent.

CONCLUSIONS

As demonstrated, variations in traffic control policies can influence fuel consumption and vehicle emissions, in addition to the traffic operational characteristics. It is now incumbent upon the practicing traffic engineer and the urban planner to consider these factors in defining policies that influence the design and implementation of surface transportation systems.

Available data relating rates of fuel consumption and emissions to vehicle operations indicate that these rates are extremely sensitive to vehicle acceleration and, to a lesser degree, to vehicle speed. To obtain accurate estimates of energy consumption and vehicle emissions requires that both operational measures be considered. The extended UTCS-1 model, because of its microscopic approach, is a valuable tool for obtaining these estimates for urban traffic. In the application presented, it was found that the RTOR policy provided both operational benefits and reductions in energy consumption and emissions, over a wide range of traffic volumes, for a representative urban network.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Karl Hergenrother of TSC who provided much insight into this model along with the fuel consumption data base, and of Nancy Rosenfield of KLD who programmed a significant portion of the FUEL module. This effort was accomplished under subcontract to Alan M. Voorhees and Associates, Inc., in support of a study sponsored by the Federal Highway Administration. Hugh McGee is the principal investigator for the study. Justin True of the Traffic Systems Division is contract manager.

REFERENCES

1. P. Kunselman et al. Automobile Exhaust Emission Modal Analysis Model. Environmental Protection Agency, EPA-460/3-74-005, 1974.
2. H. T. McAdams. Automobile Exhaust Emission Modal Analysis Model Extension and Refinement. Environmental Protection Agency, EPA-460/3-74-24, 1974.
3. A Study of Emissions From Light Duty Vehicles in Six Cities. Automotive Environmental Systems, Inc., 1973.
4. Analysis of 1973 Automobiles and Integration of Automobile Components Relative to Fuel Consumption. Transportation Systems Center, Sept. 1974.
5. E. B. Lieberman, R. D. Worrall, and J. M. Bruggeman. Logical Design and Demonstration of UTCS-1 Network Simulation Model. HRB, Highway Research Record 409, 1972, pp. 46-56.
6. R. D. Worrall and E. B. Lieberman. Network Flow Simulation for Urban Traffic Control System, Phase II, Vols. 1-5. NTIS, Springfield, Va., PB 230 760, 230 761, 230 762, 230 763, 230 764, March 1973.
7. SIGOP: Traffic Signal Optimization Program. Traffic Research Corp., Sept. 1966.
8. D. I. Robertson. TRANSYT: A Traffic Network Study Tool. Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 253, 1969.