(0.1108 gal/vehicle mile)(3600 vehicles)(4 miles)
+ (0.0772 gal/vehicle mile x 10 386 vehicles
+ 0.1772 gal/vehicle mile x 276 vehicles + 0.3784
gal/vehicle mile x 138 vehicles)(3 miles) = 4304
gal/day.

Therefore, the reconstruction of the shoulder would cost 901 gal/day.

In examples B and C, the traffic that uses the shoulder is returned to the main lanes of travel during reconstruction. The only deterioration in operation would be a reduction in capacity. For these examples, the bottleneck is further downstream, and thus the freeway operating characteristics in the area would be unaffected.

SUMMARY

The conversion of a freeway shoulder to a travel lane is an immediate and low-cost solution for increasing capacity. The results are higher travel speed, lower total travel times, and reduced fuel consumption.

Problems of shoulder pavement deterioration can be lessened by limiting the use of the lane to passenger vehicles during the peak periods only. The impact of the added capacity on fuel consumption will vary, depending on geometric design, traffic conditions, and use of the shoulder lane.

The reconstruction of a shoulder lane after several years of travel may be necessary. However, the daily fuel consumption during the period of reconstruction should not exceed the amount saved during the use of the shoulder for travel.

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Vehicular Fuel-Consumption Maps and Passenger Vehicle Fleet Projections

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The procedures and preliminary results of a study aimed at assessing the fuel-consumption characteristics of passenger vehicles that are representative of the current and near-future fleet in order to update the fuel-consumption models of computerized traffic simulation and optimization programs are presented. The paper identifies 21 engine-drivetrain combinations that are representative of 74 percent of the 1979-1985 passenger vehicle fleet and describes an instrumentation system that permits the collection of the microscopic on-the-road and laboratory test data necessary to fully assess the real-world fuel-consumption characteristics of vehicles.

The problem that this paper discusses is very simple to state: How can we reduce fuel consumption from vehicles operating on a street network? Unfortunately, the answers are quite complex.

Resolving this problem requires a dual approach. First, we need more energy-efficient vehicles; second, we need a means of accurately estimating and predicting fuel consumption from vehicles that operate on a network in order to accurately assess the energy impacts of different traffic-control strategies and roadway designs.

Breakthroughs in technology achieved by automotive engineers have provided the means of manufacturing more energy-efficient vehicles. Today automobiles that average 25-35 miles/gal (10.6-14.8 km/L) are common (1). The problems that still remain for the transportation engineer are how to assess and predict vehicular fuel consumption in any given operating environment and how to enhance roadway designs and traffic-control strategies in order to provide an environment where vehicles can operate more efficiently.

The Federal Highway Administration (FHWA) and others have developed computer programs that evaluate geometric designs and traffic-control strategies (primarily for urban areas) from environmental and energy conservation standpoints. Use of these models by many users has demonstrated their potential as effective tools in the development of traffic engineering measures that reduce motorist operating costs; fuel consumption; costs associated with planning, designing, and implementing new traffic-

Table 1. Engine-drivetrain combinations to be representative of 74 percent of the 1979-1985 passenger vehicle population.

Engine Size (in^3 of displacement)	Cylinders	Transmission[a] and No. of Forward Gears
90	4	A3 and M5
97[b]	4	A3 and M4
105	4	A3 and M5
107	4	A3 and M5
108	4	A3 and M5
140	4	A3 and M4
151	4	A3
156	4	A3
173	6	A3
200	6	A3
229	6	A3
231	6	A3
267	8	A3
302	8	A4
350[b]	8	A3

Note: 1 in^3 = 0.016 L.

[a] A = automatic and M = manual transmission.

[b] Diesel-powered engines.

control strategies; and costly and inconvenient retrofits when problems in a strategy are detected only after implementation.

These computer programs can be categorized into three major groups:

1. Simulation models: Models that simulate the performance of traffic under a given set of geometrics and control strategies (NETSIM, TRAFLO, TRANSYT, and SIGOP).
2. Optimization programs: Programs that optimize traffic signal settings by maximizing through bandwidth or by reducing delay and fuel consumption (SOAP, PASSER, MAXBAND, TRANSYT, and SIGOP). (Note, TRANSYT and SIGOP contain simulation capabilities.)
3. Control programs: Programs that control traffic signal settings based on traffic-flow fluctuations and/or time-of-day operation on a real-time basis (UTCS Enhanced and UTCS Extended).

The simulation models and the optimization programs are further subdivided into macroscopic or microscopic models, depending on the level of detail that the programs simulate traffic. For example, macroscopic programs simulate traffic in platoons or groups, while microscopic models simulate the performance of each vehicle independently.

Although most of these computer programs have been developed sporadically over the past 10-15 years, most of them use fuel-consumption models that represent the fuel-consumption characteristics of the vehicle fleet of the 1960s and/or early 1970s.

The energy crises of 1973-1974 and 1979, in addition to the 1977 Clean Air Act Amendments, triggered changes in the vehicle manufacturing policy. New vehicles are to be smaller, lighter, cleaner, and, most important, more energy efficient. In a short time, these policy changes have made the fuel-consumption models obsolete.

SOLUTION

FHWA, recognizing the need to update such models, is currently sponsoring the study, Fuel Consumption and Emission Values for Traffic Models. The scope of the study is to determine vehicular fuel consumption and emissions for the passenger vehicle fleet exclusively in two phases. Phase 1 is already completed and phase 2 is currently under way.

Phase 1: Current and Near-Future Vehicle Fleet

The main objectives of phase 1 were to define the current and near-future passenger vehicle fleet and to determine the vehicles for which fuel-consumption and emission maps (graphical representations of the relations between variables that effect fuel consumption and emissions) should be developed.

To make the study cost effective, the boundaries of the time frame that define "current" and "near future" had to maximize the period of time for which the fuel-consumption and emission tables would be valid. Based on this constraint, 1979 was selected as the lower boundary and 1985 as the upper boundary for the following reasons:

1. Between 1975 and 1977, vehicle manufacturers responded to the energy crisis of 1973-1974 by manufacturing more fuel-efficient vehicles than those manufactured before 1973. Unfortunately, this manufacturing policy started to fade in 1976 and 1977, and by 1979 most vehicles manufactured in the United States were eight-cylinder-engined vehicles (2).
2. In 1979, a second energy crisis convinced the U.S. vehicle manufacturing industry and the general public of the severity of the energy problem.
3. As of May 1981, none of the manufacturers of foreign or domestic vehicles had developed product plans beyond 1985 (3).

After determining that 1979-1985 would define the current and near-future passenger vehicle population, all the passenger vehicles that were and will be manufactured and sold in the United States (including domestic and foreign) during that time were investigated. These vehicles were defined by engine size (displacement) and engine-drivetrain combination (engine and transmission) instead of by model because of the availability of different engine sizes and transmissions within the same vehicle model.

The 1979-1985 passenger vehicle population was divided into two groups--the 1979-1981 population and the 1982-1985 population. The 1982-1985 population was defined in terms of the 1979-1981 population so that fuel-consumption and emission maps could be developed for the nonexistent vehicles.

From an analysis of the 1979-1981 passenger vehicle population, 57 engine sizes were identified, which ranged from 70 to 368 in^3 (1.1-6.0 L) of displacement. These engines were in 176 vehicle models, which yielded more than 500 engine-drivetrain combinations (transmissions were classified as automatic or manual and by the number of forward gears) (2,4). Of these 500 engine-drivetrain combinations, more than 350 combinations will be available between 1982 and 1985 (3).

It is not cost effective to develop fuel-consumption and emission maps for more than 350 engine-drivetrain combinations, so accurate sales figures were used as weighting factors to determine the most common combinations in the 1979-1985 passenger vehicle population (2,3). (Note, confidential figures were submitted by the vehicle manufacturers to the National Highway Traffic Safety Administration for corporate automobile fuel economy certification.) From an analysis of these data, 21 engine-drivetrain combinations were identified to account for 74 percent of the 1979-1985 passenger vehicle population.

Because of budget limitations, 15 of the 21 engine-drivetrain combinations will be selected for testing in phase 2 (Table 1). In the worst case, where the 15 combinations selected for testing are the "less common", the resulting fuel-consumption maps will be representative of 57 percent of the 1979-1985 passenger vehicle population. In the best case, where the 15 combinations selected are the "most common", the resulting fuel-consumption maps will be representative of 66 percent of the 1979-

1985 passenger vehicle population. Maximizing the percentage of representation will be attempted; however, the final selection of vehicles will depend on their availability from rental and leasing agencies.

The development of fuel-consumption and emission maps representative of the entire automobile fleet requires that individual tables be developed for each category--four-, six-, and eight-cylinder vehicles--and subsequently pooled by using sales figures as weighting factors. The resulting table is then statistically representative of the automobile fleet.

Projections indicated that, if the vehicle manufacturers remain relatively close to the 1981-1985 product plans developed in 1981, the fuel-consumption and emission maps to be developed in phase 2 will be valid, as a minimum, until 1992. This rationale is based on several factors. First, since 15 maps will be developed by using the pooling procedure discussed above, periodic updates could be made without having to develop additional maps; second, projections indicate that prior to 1987, non-gasoline-powered engines will not constitute a significant share of the automobile fleet; and third, as of June 30, 1981, the median age of automobiles has increased from 4.9 to 6.0 years in a decade (5).

Phase 2: Development of Fuel-Consumption and Emission Maps

The objective of this phase is to develop accurate fuel-consumption and emission maps for 15 of the 21 engine-drivetrain combinations specified in phase 1. For simplicity, the development of the fuel-consumption and emission maps will be discussed separately.

Development of Fuel-Consumption Maps

To assess vehicular fuel consumption requires the analysis of three basic systems: the engine, the vehicle (which includes body and engine), and the driver. This paper exclusively discusses the first two systems because the driver (the system that controls the operation of the engine and the vehicle) is simulated by the computerized traffic programs. In other words, the computer programs that simulate traffic take the role of the driver by using car-following algorithms derived from driver behavior. This implies that the fuel-consumption maps to be developed in this study must cover the range of speeds and accelerations that the vehicles are capable of so that fuel consumption can be accurately estimated for any driving cycle.

A requirement of the study is that the fuel-consumption maps to be developed must reflect the fuel consumption of the vehicle as it operates on realistic real-world conditions. This requirement is only accomplished by on-the-road testing.

In the past, research has been oriented toward developing fuel-consumption and emission maps from computer simulations of engine performance or chassis dynamometer testing. These approaches produce accurate maps that describe the performance of the engine exclusively and not the performance of the vehicle as it operates on the road. This, then, justifies developing maps from field experimentation.

The engine and the vehicle must be analyzed as two separate systems because the engine is the element that actually consumes fuel and the vehicle is the medium by which loads are applied to the engine. This analysis encompasses the development of the following two separate data bases that describe fuel consumption from each system:

1. A data base developed through chassis dynamometer tests that relates fuel flow to engine speed [revolutions per minute (RPM)] and manifold vacuum. This data base describes the engine.
2. A road-test data base that relates vehicle speed and acceleration to engine RPM, manifold vacuum, fuel flow, and operating temperatures for each gear. This data base describes the vehicle.

Maps derived from chassis dynamometer testing are extremely useful because fuel-flow rate is identified uniquely by engine RPM and manifold vacuum independent of the secondary effects of temperature and atmospheric pressure on the combustion efficiency itself. The resultant maps are independent of driveline efficiencies, lubricant temperatures, and rolling resistance because any changes in these parameters will change the manifold vacuum pressure at a given RPM.

At low speeds and high accelerations, the combined effects of fuel sloshing in the carburetor bowl and the time lags induced by the filtering effects of the bowl make it impossible to draw any conclusions concerning fuel-flow rate into the engine. On the dynamometer, fuel sloshing effects are negligible, and it is possible to remain at any operating point sufficiently long to overcome the filtering effects of the carburetor bowl.

On-the-road testing of vehicles is necessary to assess vehicular fuel consumption in the vehicles' operating environments. These tests consist of fully instrumenting each vehicle and driving it through combinations of speed and acceleration until sufficient data have been collected to fully characterize the behavior of the vehicle. To obtain statistically valid results, the tests are repeated several times by randomizing the order of the individual runs to prevent any systematic bias in the recorded data.

The instrumentation installed in the vehicles consists of the data logger (which samples and records data), fifth-wheel assembly, inclinometer, electronic tachometer, pressure transducers, electrical thermocouples, fuel-flow meter, and power supply.

The data logger records each data element every 0.05 s on a cassette tape that is later analyzed in a computer. The fifth-wheel assembly measures distance, speed, and acceleration, and the inclinometer measures road grades to correct the acceleration readings to what they would have been on a level road. The electronic tachometer, pressure transducers, and electrical thermocouples measure engine RPM, vacuum pressure, and engine temperature, respectively. The equipment weighs approximately 150 lb (68 kg) and fits in the rear passenger area of a vehicle.

On-the-road tests are being conducted on an airport runway because of the safety advantages over conducting the tests on public roads. The tests require the collection of fuel-consumption data for high speeds and abrupt accelerations, and this might be hazardous if carried out on public roads. In addition, conducting the tests on a smooth, leveled pavement increases the accuracy of the data collected by the fifth-wheel assembly. Bumps, cracks, potholes, and joints in pavements make the fifth wheel bounce, which results in erroneous measurements of speed, acceleration, and distance.

It is important to point out that the resulting maps will be sensitive to ambient temperature. It is not possible to define and test at a single normal operating temperature without imposing some, possibly quite severe, limitations on the applicability of the test results. The use of fuel-consumption maps generated at 70°F (21°C) ambient temperature to calculate fuel use by winter traffic in Minneapolis-St. Paul, for example, could easily result in errors greater than 20 percent. Furthermore, data available in the current literature are not of sufficient detail to permit an analytical correction of the maps for ambient temperature with the necessary confidence.

The approach taken to resolve this problem is to test a vehicle over a bandwidth of ±20°F (±11°C) around a preselected value of 50°F (10°C). The data collected from this vehicle will be used to define an ambient temperature sensitivity curve from which values could be extrapolated for all other vehicles tested. This would result in the development of temperature-sensitive fuel-consumption maps that are representative of the automobile fleet. Preliminary results indicate a reduction of approximately 0.4 percent in fuel consumption per degree centigrade increase. [Note, this is for ambient temperatures around 70°F (21°C). It is expected to vary for different temperatures.]

Subsequently, the data bases generated by the dynamometer testing and the on-the-road testing are merged and run through statistical mapping procedures to produce maps that relate fuel-flow rate to vehicular speed and acceleration for each available gear.

Before the actual development of the maps, the raw data are reformatted by performing the following manipulations in a computerized preprocessor:

1. The data collected are simultized in time. The data logger records each data point sequentially and not simultaneously as desired. This implies that there is discontinuity in the data collected caused by the time lag of the sampling rate. To correct this problem, the data are slightly adjusted and fitted through a least-squares estimated quadratic function of the parameter over time. The result is a continuous function of the parameters as if they would have been collected simultaneously.

2. The acceleration readings are adjusted to what they would have been on a level road by using

Figure 1. Dynamometer fuel-flow observations, neutral gear.

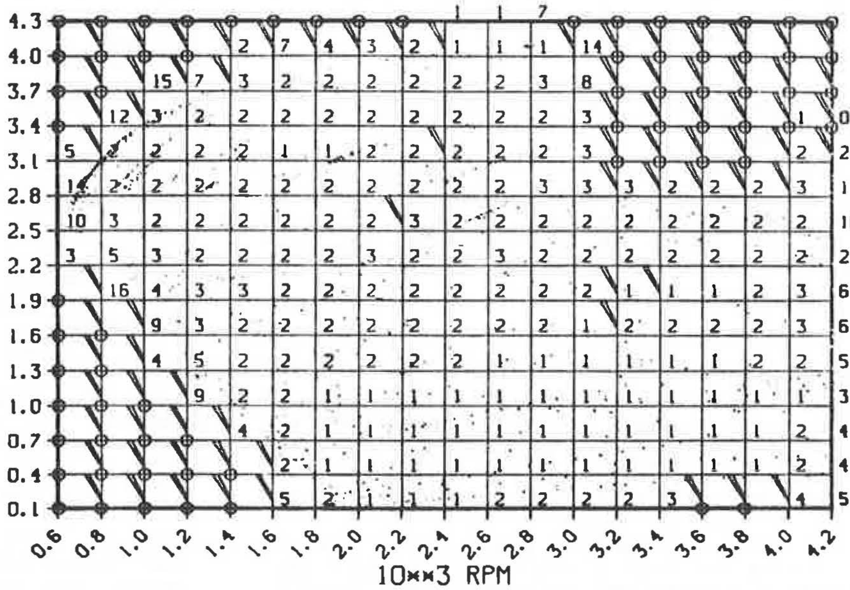


Figure 2. On-the-road fuel-flow observations, first gear.

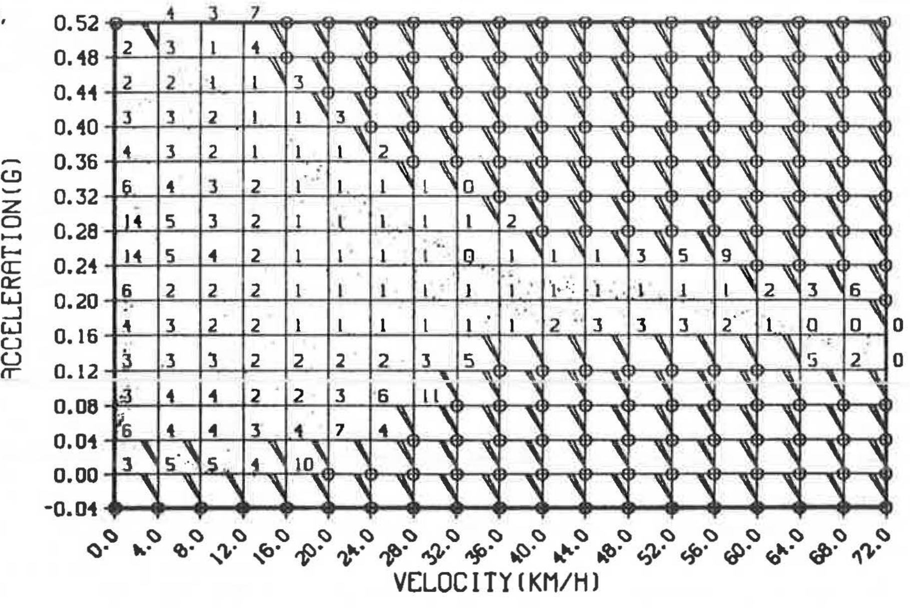


Figure 3. On-the-road fuel-flow observations, second gear.

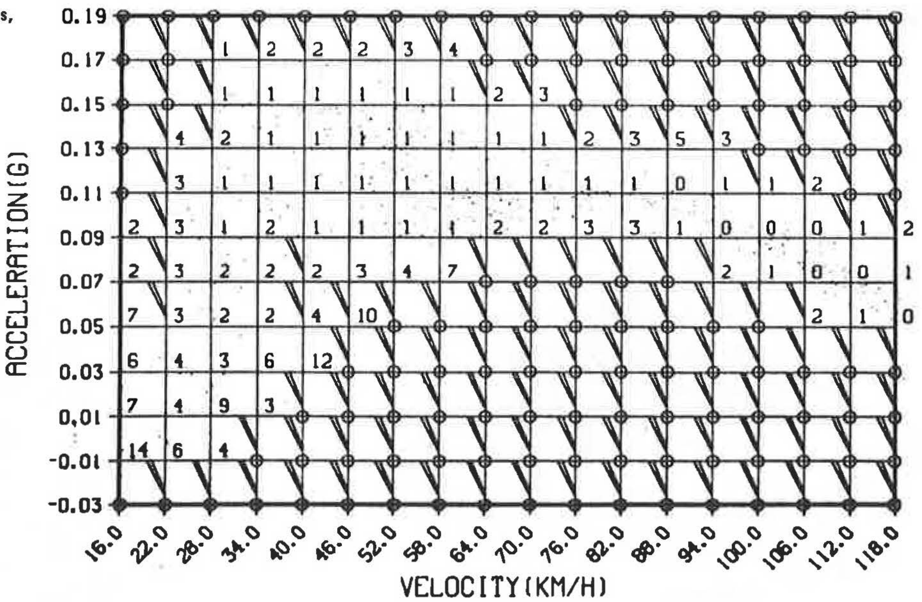
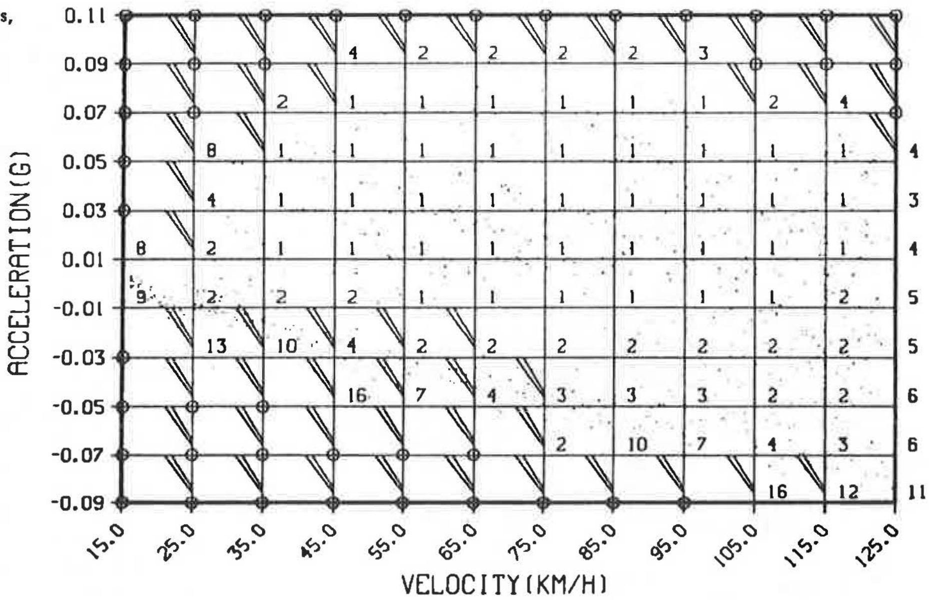


Figure 4. On-the-road fuel-flow observations, third gear.



the inclination readings. If the tests are run on a level road, this step is not necessary, as the inclination reading (total newtonian acceleration) may be substituted for the acceleration.

3. The fuel-flow values derived from dynamometer testing are inserted into the on-the-road data base by using engine speed (RPM) and manifold vacuum as the common parameters between laboratory and field testing.

4. The gears are inserted into each on-the-road observation based on the observed ratios of engine RPM over velocity. For vehicles with automatic transmission, ambiguous ranges of ratios occur that fall into several gears. In these overlap cases, the current and preceding observations of RPM, manifold vacuum, and fuel flow are checked to see if a gear change took place in the time interval between observations.

Following these manipulations, the actual development of the maps can be undertaken. For simplicity, the development of the maps is discussed by using data collected from a 200 CID Ford Fairmont station wagon equipped with automatic transmission. (Note, the following seven figures were derived from data collected from this type of station wagon.)

The laboratory and on-the-road data are placed on a grid with suitable intervals that relate fuel consumption to engine RPM and manifold vacuum, as shown in Figure 1. By merging the laboratory and on-the-road data as previously discussed, fuel consumption is then related to velocity and acceleration by using engine RPM and manifold vacuum as the common parameters between the tests, as shown in Figures 2 through 4, for each available gear.

The scatter points represent the individual observations from which the maps were constructed (789 in gear 1, 686 in gear 2, and 2526 in gear 3). The intersection of the grid lines represent the poles around which a quadratic surface is fitted. The size of the region over which the fit is made depends on the data density and usually has a width of

Figure 5. Fuel use (mL/s), bicubic spline, first gear.

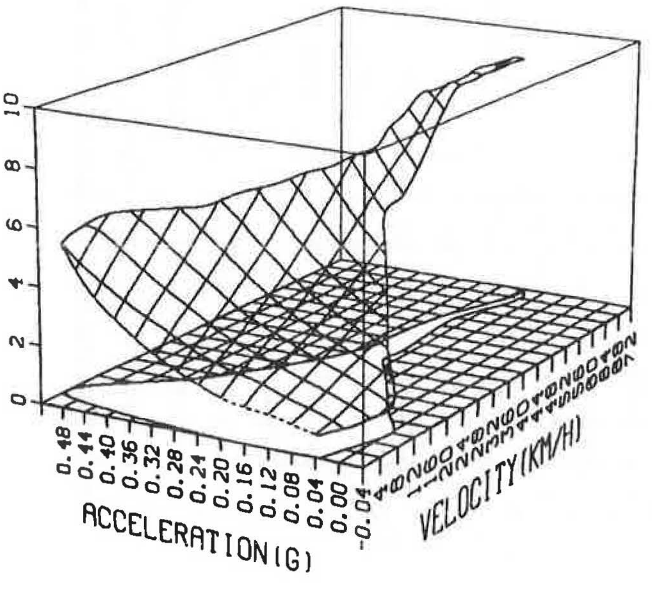
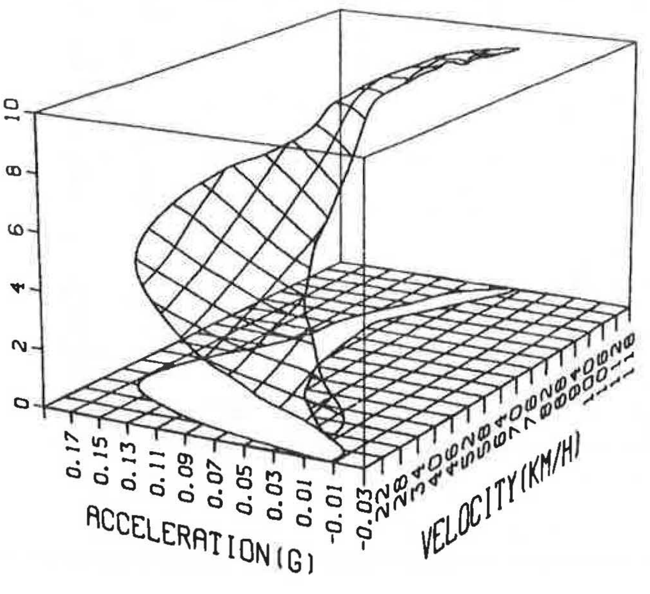


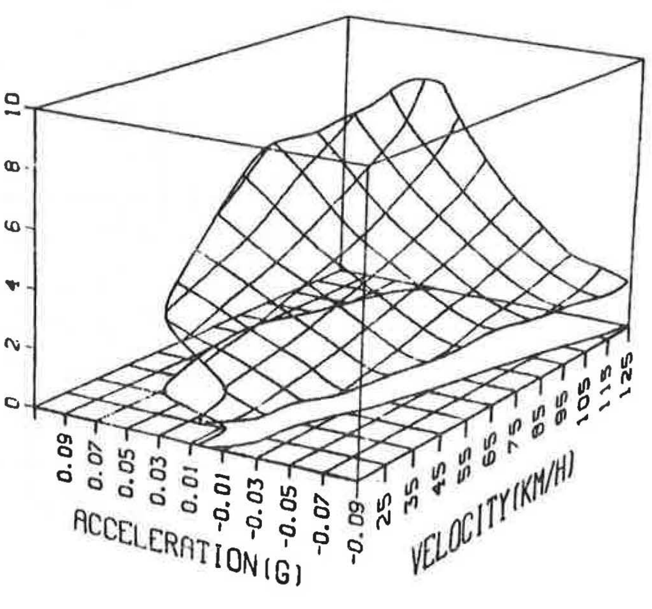
Figure 6. Fuel use (mL/s), bicubic spline, second gear.



2-4 grid squares. The resultant quadratic is used to estimate fuel use at each pole and to estimate the confidence interval for each estimate. The small circles highlight poles that were not estimated either because of lack of data or due to numerical problems (primarily matrix singularities) (6).

The numbers inside the boxes pertain to the pole at the lower left corner of the rectangle and represent a measure of the quality of the fit of the quadratic surface to the underlying data. A 2, for example, indicates that one can have a 90 percent confidence that the mean of the actually observed flow rates is within 2 percent of the predicted value. In the event that the calculated confidence intervals are not within acceptable limits, the grid pattern could be changed in the hope that this will improve the quality of the fit. If changing the grid pattern results in no improvement, then the required procedure is to collect additional data on the dynamometer or test track, as appropriate.

Figure 7. Fuel use (mL/s), bicubic spline, third gear.



Provided that the quality of the quadratic fits is satisfactory, a bicubic spline surface is run through the poles of the quadratic fits, which results in a smooth surface like that of Figures 5 through 7 for each gear. The diagonal stripes mark rectangles for which satisfactory bicubics could not be derived. If one or more of the poles that surround a striped rectangle is encircled, no bicubic could be estimated, since an underlying quadratic was missing. Otherwise, a bicubic was estimated but failed to come within 1 percent (3 percent for the dynamometer maps) of the underlying surface with 90 percent confidence. Failure of the 1 percent level test, on occasion, has been caused by a quadratic that differs slightly from the others that surround it instead of a poor bicubic fit. Again, this problem would be resolved by changing the grid size or collecting additional data, although a more cost-effective procedure is to extend one of the adjacent bicubics to cover the poorly fitting area. The step of calculating the bicubics is required because the quadratic surfaces were estimated independently, therefore introducing discontinuity at their junctions. Aside from the bicubics fitting the dynamometer data, most bicubics that fail the 1 percent tolerance unit test pass it at 2 or 3 percent tolerance.

Development of Emission Maps

The relatively long response times of current emission analyzers coupled with their bulk, weight, and high power requirements relegate any testing program to one of steady-state determinations on a chassis dynamometer. In this study, it is anticipated that test procedures for hydrocarbon and carbon-monoxide emissions can be developed that are analogous to and compatible with those used for the fuel-consumption tests. That is, if each engine operating point, as defined by engine RPM and manifold vacuum, determines the emission rates of the vehicle (subject to verification through this study), then emission maps can be developed on the dynamometer that can be linked to on-the-road performance through measurements of the determining factors in an on-the-road test in a manner similar to the methodology used in developing the fuel-consumption maps.

SUMMARY AND RECOMMENDATIONS

From a transportation perspective, the scenario for the 1980s is restricted by energy and environment concerns. The era of abundant energy supplies is past, and reducing air pollution is imperative. It is time to work with greater commitment and urgency toward implementing environmentally safe and energy-efficient solutions.

In the United States, it has been estimated that all modes of highway transportation account for 74 percent of the total transportation energy and 45 percent of all U.S. fuel consumption (7). In addition, it has been estimated that highway transportation accounts for 50 percent of the total annual emissions of air pollutants such as carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides, and particulates (8). These statistics dramatically demonstrate the seriousness of the energy and environmental problems as related to highway transportation.

Future research should be oriented toward developing fuel-consumption and emission maps for trucks and buses in a manner similar to the one described in this paper. Also, efforts should be directed toward developing feasible roadway design practices that would provide an operating environment where vehicles could operate efficiently.

To cope with environmental and energy problems, major traffic engineering actions, which require accurate analysis tools, must be planned and pursued aggressively over many years. The successful completion of this study will update and improve the capabilities of the traffic models in accurately estimating fuel consumption and emissions from passenger vehicles that operate in a street network. This enhancement will provide the traffic engineering community with powerful tools for developing, testing, and evaluating traffic-control strategies in addition to determining the environmental and energy impacts of such strategies.

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Effect of Freeway Work Zones on Fuel Consumption

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The objective of this study was to investigate the effect of freeway work zones on fuel consumption. The development of a procedure for estimating the excess fuel consumption caused by lane closures on 3-, 4-, and 5-lane freeway sections is presented. The procedure is applicable to both undersaturated and oversaturated traffic-flow conditions. Tables and graphs designed to facilitate the implementation of the procedure are included. An example that illustrates the application of the procedure is also presented.

The excess fuel consumption associated with the movement of traffic through work zones is a major factor in the increased operating expense to the highway user. In recent years, there has been a shift of priorities at all levels of government from building new highway facilities to upgrading the existing highway system. At the same time, the public has become increasingly aware of the need to conserve energy due to the increasing costs associated with that energy. In light of these facts, the prudent engineer must consider the effect of work zones on fuel consumption.

A development of user costs associated with construction activities was presented by Graham and others (1) in a Federal Highway Administration (FHWA) report completed in June 1977. Formulas were developed from curve fits, which resulted in equations for excess fuel consumed as a function of average daily traffic (ADT) for various combinations of lane-closure configurations and schedules. Although the report provided useful information on fuel consumption in a general sense, no method for computing the fuel use for site-specific lane-closure schedules and hourly volumes was presented.

The purpose of the study presented in this paper was to investigate the impact of freeway work zones on fuel consumption. This impact was evaluated for the following lane-closure situations:

1. Two unidirectional lanes reduced to one lane,
2. Three unidirectional lanes reduced to two lanes,
3. Three unidirectional lanes reduced to one lane,
4. Four unidirectional lanes reduced to three lanes,
5. Four unidirectional lanes reduced to two lanes, and
6. Five unidirectional lanes reduced to two lanes.

This paper presents the development of a procedure for estimating the excess fuel consumption caused by these freeway work zones during both undersaturated and oversaturated traffic flow conditions. Tables and graphs designed to facilitate the calculation of these estimates are included, and an example that illustrates the application of the procedure is presented.

UNDERSATURATED CONDITIONS

During time periods when the volume-capacity ratio