PART 1

Energy

Estimating Automobile Fuel Consumption in Urban Traffic

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A study conducted to develop fuel consumption models for passenger cars in the urban traffic of Singapore is described. The models were developed using multiple-trip travel data derived from a survey involving 114 cars. Each participating car went through three survey cycles; each cycle covered at least 300 km (186 mi). The entire survey generated 11,557 trips. The day-to-day vehicle usage and travel patterns of participants during the period of survey were not affected by participating in the survey. Altogether 16 makes of cars were represented. Three categories of data were recorded: vehicle information, fuel consumption, and trip diary. The fuel consumed in each survey cycle was derived from pump readings. Special measures were taken in survey design and gasoline refueling to ensure sufficient accuracy in fuel measurements. Test results indicate that the survey approach can be used to calibrate a basic average-speed fuel consumption model, and the survey data could be used effectively to identify the effects of vehicle-specific parameters and climatic conditions on fuel consumption.

Many automobile fuel consumption models have been proposed by various researchers. These models can be classified into two broad categories: (a) instantaneous models that relate fuel consumption to the time history of speed variations, and (b) average-speed models that estimate fuel consumption from average speeds of trips (*1*,*2*). Instantaneous models are suitable for fuel consumption studies that deal with individual intersections or road sections for which detailed information on speed variations can be obtained reliably. Average-speed models are useful for assessing total fuel consumptions in large road networks for which detailed vehicle and journey information for individual trips is not readily available.

This study adopts the average-speed approach to model automobile fuel consumption in Singapore City. Fuel consumption models are established using aggregated multiple-trip travel data derived from a survey involving 114 cars. A unique feature of this survey was that no special-purpose fuel consumption measurement device was instrumented to measure the fuel consumed in each individual trip. Instead, the fuel consumed by each vehicle was derived from pump readings when the fuel tank of the vehicle was filled during the survey period. The feasibility of using this approach to calibrate a fuel consumption model for actual traffic conditions is examined in this paper.

BASIS FOR CALIBRATION OF FUEL CONSUMPTION MODELS

This section explains the extension of basic average-speed models for single trips to cover the multiple-trip survey of this study in which only the final total fuel consumptions of sets of multiple trips are known. This forms the basis on which the field survey of this study was designed to provide the necessary data for calibrating fuel consumption models.

The most basic form of average-speed model for automobile fuel consumption in urban traffic conditions correlates fuel consumption with the reciprocal of average journey speed (*3–6*):

$$F = a_0 + \frac{a_1}{V} \qquad (1)$$

where

F = average fuel consumed for a unit distance in a trip,
V = average speed of the trip, and
a_0, a_1 = vehicle-specific coefficients.

Coefficient a_1 is commonly taken to be an estimate of vehicle idle fuel rate, and coefficient a_0, to be related to fuel required to overcome drag, inertia, and grade resistance (*5–8*). Equation 1 has been found to give satisfactory estimates of fuel consumption for journey speeds between 10 and 60 km/hr (approximately 6 and 37 mph).

In addition to the speed variable, studies have also shown that fuel consumption in urban traffic conditions can also be correlated with vehicle characteristics, such as engine capacity or vehicle mass, in an approximately linear relationship (*5*,*7*,*8*). One may, therefore, estimate fuel consumption per unit distance from the following general expression:

$$F = a_1 + \frac{a_1}{V} + a_2 K \qquad (2)$$

where coefficient a_2 and variable K represent the effect of vehicle operational characteristics.

Equations 1 and 2 provide an estimate of the fuel consumed by a vehicle in a single trip. For a trip i with trip length and average speed equal to L_i and V_i, respectively, the total fuel consumed for the trip is

$$F\,L_i = a_0 L_i + a_1 \frac{L_i}{V_i} + a_2 K\,L_i \qquad (3)$$

The fuel consumed by the same vehicle for a total of N trips is given by

$$\sum_{i=1}^{N} F\,L_1 = \sum_{i=1}^{N} a_0 L_i + \sum_{i=1}^{N} a_1 \frac{L_i}{V_i} + \sum_{i=1}^{N} a_2 K\,L_i \qquad (4)$$

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Fuel consumption rate F can be derived by dividing the expression in Equation 4 by the total distance traveled, L_T, as follows:

$$F = \frac{1}{L_T}\left\{\sum_{i=1}^{N} F\, L_i\right\}$$

$$= a_0 + a_1 \left\{\frac{1}{L_T}\sum_{i=1}^{N}\frac{L_i}{V_i}\right\} + a_2K \qquad (5)$$

The second term in the right-hand side of Equation 5 can be simplified as follows:

$$a_1\left\{\frac{1}{L_T}\sum_{i=1}^{N}\frac{L_i}{V_i}\right\} = a_1\left\{\frac{\frac{L_1}{V_1}+\frac{L_2}{V_2}+\cdots+\frac{L_i}{V_i}+\cdots+\frac{L_N}{V_N}}{L_T}\right\}$$

$$= a_1\left\{\frac{t_1+t_2+\cdots+t_i+\cdots+t_N}{L}\right\}$$

$$= a_1\left\{\frac{t_T}{L_T}\right\}$$

$$= \frac{a_1}{V_T} \qquad (6)$$

where

t_i = travel time of trip i,
$t_T = \Sigma_{i=1}^{N} t_i$ = total sum of travel times of N trips, and
$V_T = \frac{L_T}{t_T}$ = average speed for N trips.

Equation 5 can therefore be represented simply as

$$F = a_0 + \frac{a_1}{V_T} + a_2 K \qquad (7)$$

The coefficients a_0, a_1, and a_2 in Equation 7 are identical to the corresponding coefficients of Equation 2. This is of practical significance because virtually all controlled fuel consumption experiments reported used trip-specific data and trip-specific relationships (such as Equation 2) to calibrate fuel consumption models. The given derivation shows that the same form of models could also be calibrated from Equation 7 using aggregated fuel consumption and travel data that cover multiple trips.

The use of Equation 7 allows the volume of fuel consumed to be measured after many trips have been made. This reduces considerably the level of accuracy needed to achieve in each fuel volume measurement. The fuel consumption rate, F, in Equation 7 is computed by dividing the total fuel consumption over N trips by the total distance traveled in as many trips. The average speed, V_T, is obtained as the ratio of total distance traveled to the sum of travel times of all N trips. It can be shown that V_T is numerically equal to the travel-time weighted average of trip average speeds.

DESIGN OF SURVEY

A major objective of the present study was to calibrate an aggregate average-speed fuel consumption model for the urban traffic of Singapore based on actual travel patterns of survey participants in actual traffic conditions.

The entire design of the survey revolves round the choice of a so-called survey cycle. A survey cycle defines the time period over which appropriate aggregated fuel consumption and travel characteristics data are measured. Because no special fuel measurement device was used in this study, and because the amount of fuel consumed was to be derived from pump readings, a logical choice of survey cycle was one that began from the time the fuel tank of a study vehicle was filled to the time of the next fill-up.

Length of Survey Cycle

It is desirable to have a survey cycle cover more than a week so that the effects of weekday and weekend travel would both be incorporated. Too long a survey cycle is undesired as it may impose undue stresses on the participants. From considerations of the travel patterns of local car users and the fuel tank capacity of normal makes of car in Singapore, it was decided that a survey cycle should cover a total travel distance of at least 300 km (186 mi). For most survey participants, a survey cycle could be completed between 1 and 2 weeks. On the average, each cycle would consume about 30 L (7.93 gal) of gasoline.

Recording of Survey Data

Each survey participant was required to go through three consecutive survey cycles. In each cycle, three categories of data were recorded: vehicle information, fuel purchase, and trip diary. The vehicle information covers year of manufacture, original vehicle registration date, make, model, engine capacity, curb weight, type of transmission and steering, air conditioner, and tire type. Fuel purchase data were recorded during each visit to the service station for filling up the fuel tank. The data entered were unit fuel price, total purchase price, total purchase volume, petrol brand and grade, vehicle odometer reading, and time and date of purchase. The trip diary contains detailed information of each trip in a survey cycle. The trip information includes the date, the times and odometer readings at the start and the end of each trip, the number of adults and children carried, estimates of the proportions of trip distance by type of road taken, and trip purpose.

A trip was considered to have commenced once the engine was switched on. The time period during which the vehicle engine runs continuously, inclusive of idling and moving phases, defines the travel time of the trip. The travel distance of each trip is derived from odometer readings in the trip diary.

Fuel Consumption Measurement

The quantity of fuel consumed in each survey cycle of a vehicle is equal to the amount of fuel needed to fill its fuel tank again at the end of the trip. As illustrated in Figure 1, the study required a survey cycle to begin and end at a service station at which refueling took place. For each participating vehicle, there were four refueling sessions. The first refueling established the so-called full-tank condition that defined the fuel level that each refueling must reach. The amounts of fuel consumed in the first, second, and third cycles were equal to the respective quantity purchased in the second, third, and fourth refuelings.

In view of the importance in ensuring that the same fuel level was reached in each refueling, a set of instructions was specially prepared describing in detail the steps to be taken during refueling. Each participant was asked to identify visually a reference mark on the wall of the outlet tube leading to the fuel tank. Refueling to this reference mark was to be achieved in a two-step procedure. First, participants were to start refueling by selecting the full-tank option of the gasoline pump. At the end of this step, when the pump stopped automatically, the fuel tank would still be able to take in another 1 to 2 L of gasoline. The second step therefore involved manually operating the pump to bring the fuel to the reference mark.

Survey Participants

The survey required considerable effort on the part of participants to record the details of every trip over 3 to 5 weeks. Great emphasis was therefore placed on selecting survey participants to ensure that quality survey data were returned. It was on this ground that the target population of survey was restricted to car owners with tertiary education qualification and who drove their cars themselves. The study included a random sample of 114 willing participants. The sample is believed to be representative of the middle-income car-owners of Singapore. It is important to note that the participants' day-to-day travel patterns and vehicle usage during the period of survey were not affected as a result of participating in the survey.

ANALYSIS OF SURVEY DATA

Because each participant went through three survey cycles, the entire survey produced a total of 342 data points for the calibration of Equation 7. The total number of trips included was 11,557. This means that there was an average of about 34 trips in a survey cycle. Altogether 16 makes of car were represented. Table 1 presents the frequency distribution of engine capacity of the cars that participated in the survey. The frequency distribution appears to provide a fair representation of the size of cars found on Singapore roads. A report by the Singapore Registry of Vehicles showed that at the end of 1989, 95.9 percent of the passenger cars and vans in Singapore had less than 2000 cm^3 in engine capacity (*9*). The main features of the travel characteristics revealed by the survey are depicted in Figure 2. Each of the three frequency distribution plots are derived from 342 data points, one point

TABLE 1 Frequency Distribution of Cars by Engine Capacity

Engine Capacity	No. of Cars	Percentage
≤ 1,000 cm^3	29	25.4
1,001 to 1,600 cm^3	81	71.1
1,601 to 2,000 cm^3	4	3.5

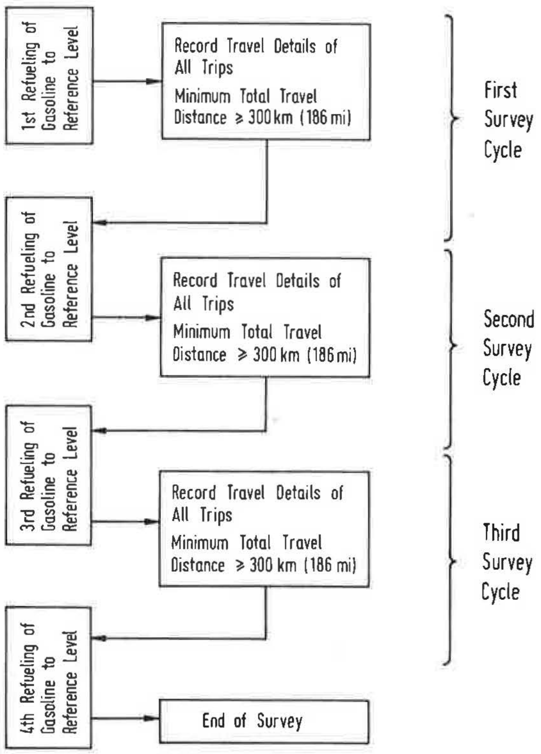


FIGURE 1 Main components of survey procedure for each participant.

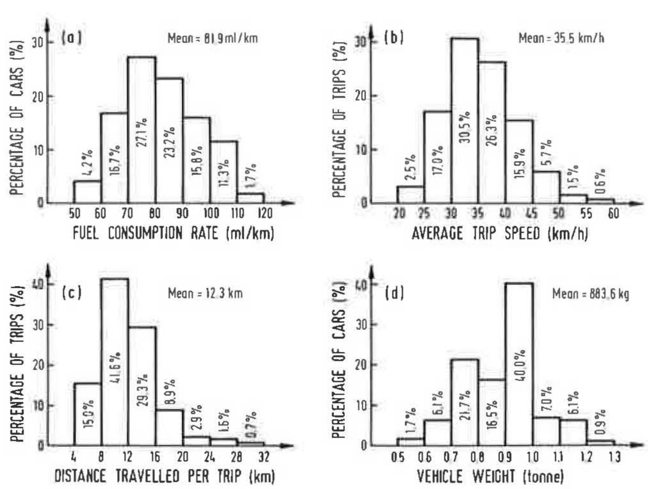


FIGURE 2 Frequency distributions of travel characteristics of cars surveyed.

TABLE 2 Summary of Statistics of Principal Variables

Variables	Mean	Standard Deviation	Minimum Value	Maximum Value
Fuel Consumption (ml/km)	82.0	13.8	50.3	118.3
Engine Capacity (cm^3)	1,293.4	248.5	665	1,998
Vehicle Weight (kg)	883.7	136.8	570	1,375
Trip Average Speed (km/h)	35.73	6.91	20.32	61.27
Passenger Load	1.74	0.487	1.00	4.75
Age of Car (years)	4.26	2.90	0.14	9.89
Odometer Mileage (km)	80,840	58,130	2,180	243,600

from each of the 342 survey cycles. The fuel consumption computed lay between 55 and 120 mL/km (approximately 20 and 50 gal/1,000 mi). The average speed varied from 20 to 60 km/hr (approximately 12 to 38 mph). Table 2 summarizes the statistics of the principal variables considered in this study.

Calibration of Basic Average-Speed Model

A regression analysis was performed to fit the basic average-speed model defined by Equation 1 to the survey data. The resulted regression equation is

$$F\ (\text{mL/km}) = 54.2 + \frac{1{,}009.8}{V_T\ (\text{km/hr})} \qquad (8)$$

or

$$F\ (\text{gal/1,000 mi}) = 23.0 + \frac{266.7}{V_T\ (\text{mph})} \qquad (9)$$

These equations have coefficients of correlation $r = .65$ and $r^2 = .42$. The relatively low r^2-value is not unexpected, because the model represented by Equation 1 is defined for a single vehicle type, whereas the survey data were derived from 114 vehicles. The regression equations therefore serve merely as an assessment of the aggregate fuel consumption characteristics of the sample of vehicles studied. Each of these vehicles was likely to have a different idle fuel consumption rate (and hence different values of coefficient a_1) and a different vehicle weight and engine capacity (and hence different values of a_0). There were therefore inherent spreads of fuel consumption performance among different vehicles. Although aggregate models such as Equations 8 and 9 cannot be used for accurately describing the fuel consumption characteristics of individual vehicles, they are useful for assessing the impact of traffic management policies on the fuel consumption of the entire traffic stream (*1,2,10*).

It is of interest to compare the values of coefficients a_0 and a_1 derived above with those obtained in other studies. Table 3 summarizes the results of a number of studies reported in the literature. It is seen that the value of a_0 varies from 43.4 to 121.8 mL/km, and the value of a_1 from 983 to 3780 mL/hr. The factors contributing to these variations include differences in vehicle design, traffic flow conditions, layout of street networks, road conditions, and drivers' behavior.

Two different forms of fuel consumption models are found in Table 3: vehicle type-specific models and traffic stream aggregate models. The vehicle type-specific models suggest that, in general, both a_0 and a_1 values increase as vehicle size becomes bigger. Equations 10, 12, and 17 in Table 3 are aggregate models that provide estimates of fuel consumption for car populations of the Netherlands, Australia, and the United States, respectively. These three models are plotted in Figure 3 along with the Singapore model derived in this study. From a comparison of the four models, the following observations can be made:

- The overall idle fuel rate (i.e., coefficient a_1) of an average car in Singapore is of the same order as the rates of small-capacity cars represented in Equations 11, 15, and 19 (see Table 3). It is considerably lower than an average car in the United States and Australia. It compares better with models in the Netherlands (see Equations 10a and 10b).
- A comparison of coefficient a_0 of the models also leads to a similar conclusion. It may be said that the drag, inertia, and grade resistance encountered by an average car in Singapore is comparable to its counterpart in the Netherlands but much lower than that in Australia or the United States.
- In general, the fuel consumption model for an average car in Singapore approximates those derived for small cars in other studies. These include the small car model (Equation 11) derived by Biggs and Akcelik for Australian cars (*2*), and Equations 15 and 19 derived by Everall (*8*) and Evans and Herman (*12*), respectively.

Further Analysis of Average-Speed Model

A verification of the average-speed model and an assessment of the validity of the fuel consumption survey procedure adopted in this study can be made by incorporating vehicle-specific variables in the analysis. Assuming that the idle fuel consumption rate of a vehicle is linearly related to its engine capacity (*4*), the following covariance model may be used:

TABLE 3 Values of Coefficients in Average-Speed Model of Equation 1

Study	$F(ml/km) = a_0 + \frac{a_1}{V\ (km/h)}$	Eq.No.	Remarks
OECD [1]	$F = 43.4 + \frac{1359}{V}$	(10a)*	Developed in 1981, average for cars on main roads of Netherlands.
	$F = 64.5 + \frac{1166}{V}$	(10b)*	Developed in 1981, average for cars on other roads of Netherlands.
Biggs and Akcelik [2, 7]	$F = 59.0 + \frac{1280}{V}$	(11)	Developed in 1985, for small cars in Australia.
	$F = 73.8 + \frac{1600}{V}$	(12)*	**Developed in 1985, for medium cars in Australia, recommended as default model for all cars in general urban environment.**
	$F = 88.6 + \frac{1920}{V}$	(13)	Developed in 1985, for large cars in Australia.
OECD [6]	$F = 70.0 + \frac{990}{V}$	(14)	Developed in 1980, for car model Renault R12.
Everall [8]	$F = 56.4 + \frac{1159}{V}$	(15)	Developed in 1968, for Vauxhall Viva, engine capacity 1057 cm^3.
	$F = 85.0 + \frac{1913}{V}$	(16)	Developed in 1968, for Ford Zephyr, engine capacity 1703 cm^3.
FHWA [10]	$F = 85.2 + \frac{2825}{V}$	(17)*	Developed in 1981, average model for USA cars.
Chang et al [11]	$F = 112 + \frac{3780}{V}$	(18)	Developed in 1976, for test car, engine capacity 6600 cm^3.
Evans and Herman [12]	$F = 45.6 + \frac{983}{V}$	(19)	Developed in 1978, for test car, vehicle weight 1035 kg.
	$F = 121.8 + \frac{2420}{V}$	(20)	Developed in 1978, for test car, vehicle weight 2488 kg.

Note: Equations marked with * are aggregate models for the entire traffic stream considered; other equations are models derived especially for specific vehicle types.

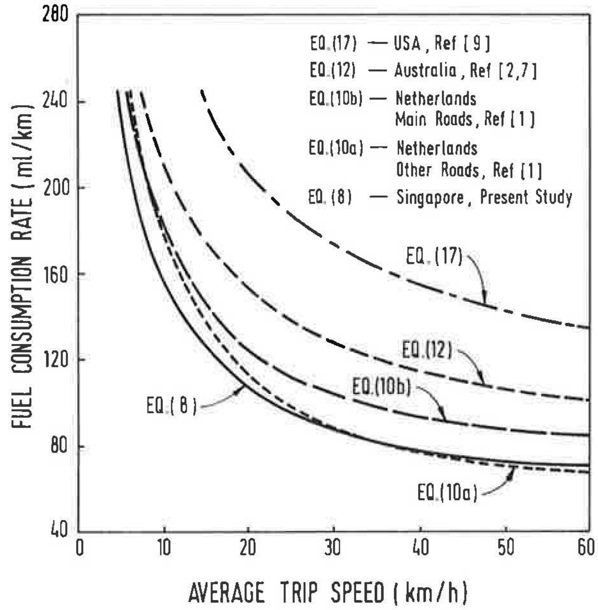


FIGURE 3 Comparison of aggregate fuel consumption model of Singapore with models of other countries.

$$F = b_0 + b_1 \left(\frac{E}{V_T}\right) + \sum_{i=1}^{113} (b_2)_i X_i \tag{21}$$

where

X_i = indicator variable that can assume a value of 0 or 1, for $i = 1, 2, \ldots 113$;
E = engine capacity (cm^3 or in^3);
b_0, b_1 = regression constants; and
$(b_2)_i$ = regression constants, for $i = 1, 2, \ldots 113$.

In Equation 21, X_1 to X_{113} are indicator variables that isolate the effects of the 114 vehicles surveyed. For any given data set, only the one X_i that represents the vehicle from which the data set was obtained can have the value 1; all other X_i terms equal 0. In other words, the fuel consumption of vehicle i is given by

$$F_i = b_0 + b_1 \left(\frac{E}{V_T}\right) + (b_2)_i \tag{22}$$

Comparing Equations 1 and 22, it is seen that $a_0 = b_0 + (b_2)_i$ and $a_1 = b_1 E$. Equation 22 can therefore be seen as a collection of fuel consumption models meant for the individual vehicles surveyed in the study.

Fitting the survey data to the regression model of Equation 21 yields a coefficient of multiple determination, r^2, equal to .89. This result lends support to the average speed model of Equation 1 and the derivation of Equation 7. It also suggests that the multiple-trip survey technique employed in this study could be effectively used to calibrate fuel consumption models.

Extended Average-Speed Models

The model of Equation 22 has limited practical application because the use of indicator variables X_i could only differentiate the effects of individual survey vehicles. It does not identify the physical parameters that are responsible for the differences in the $(b_2)_i$ coefficients, hence the differences in fuel consumption of the vehicles surveyed. Instead of using qualitative variables, a number of researchers suggested that the drag, inertia, and grade resistance experienced by a vehicle was proportional to its weight (*1,5,7,11*). This means that we can replace Equation 22 with the following model:

$$F = b_0 + b_1 \left(\frac{E}{V_T}\right) + b_2 W \tag{23}$$

where W is the vehicle weight in kilograms or pounds.

Fitting the survey data to Equation 23 by regression analysis leads to the following expression:

$$F\,(\text{mL/km}) = 33.6 + 0.7639 \frac{E\,(\text{cm}^3)}{V_T\,(\text{km/hr})} + 0.0226\,W \quad (\text{kg}) \tag{24}$$

or

$$F(\text{gal/1,000 mi}) = 14.3 + 3.3065 \frac{E\,(\text{in}^3)}{V_T\,(\text{mph})} + 0.0044\,W \quad (\text{lb}) \tag{25}$$

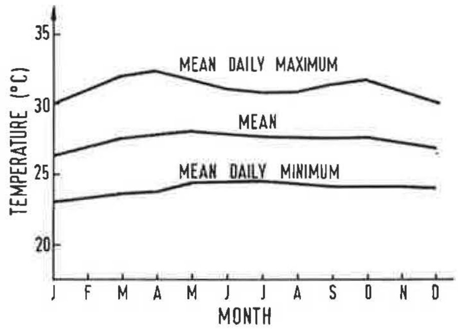
Taking W as the unladen vehicle weight in this expression yields an r^2-value of .54. Adding passenger loads to the individual survey data and entered as values of W made negligible improvement in the r^2-value. Equation 24 or 25 can therefore be used to estimate the fuel consumption in the urban traffic of Singapore for a passenger car with known engine capacity, E, and unladen weight, W.

Effects of Other Factors

Besides traveling speed, vehicle weight, and engine capacity, the survey data contain additional data allowing the effects of several other factors to be evaluated. These include effects of vehicle age, power steering, automatic transmission, and climatic conditions. Adding these factors to the model of Equation 23, however, would only improve the r^2-value from .54 to .56. For the practical purpose of fuel consumption estimation, the simple model of Equation 23 appears to be adequate. For the sake of completeness in presentation, the effects of the other factors mentioned are briefly discussed in this section.

Vehicle Age and Total Mileage Traveled

Vehicle age refers to the time in months since a vehicle was registered by the first owner. Alternatively, the total odometer mileage could be used as an indirect measure of vehicle age. These two variables were highly correlated. Either of these two variables, when included in the model of Equation 23, was found to be statistically significant at a 99 percent confidence level. The corresponding effect on fuel consump-



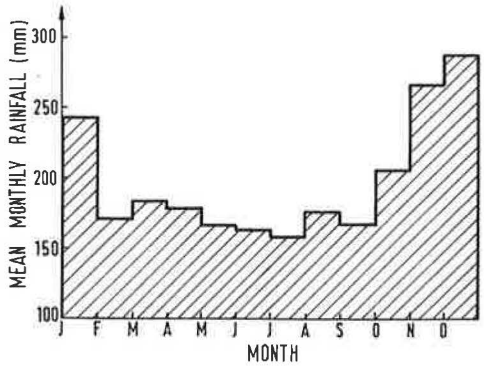


FIGURE 4 Characteristics of Singapore climate based on data from 1967–1986 (*16*).

tion rate of vehicle age was an increase of 1.53 mL/km/year, and that of total mileage traveled was 0.8 mL/km higher for every additional 1000 km—that is, the fuel consumption rate increased as the vehicle aged, or as the total mileage coverage of the vehicle became higher.

Power Steering

The effect of power steering can be included in Equation 23 by using an indicator variable that assumes a value of one if a vehicle has power steering capability and a value of zero if it has no such capability. The effect was found to be significant at 99.9 percent confidence level. The regression analysis showed that power steering on the average caused a vehicle to consume 11.3 mL/km more fuel than one without power steering.

Automatic Transmission

The effect of automatic transmission was studied by representing it with an indicator variable of the same nature as that of power steering. Regression analyses that included this variable in Equation 23 indicated that the effect of automatic transmission was also statistically significant, though at the lower confidence level of 95 percent. Vehicles with automatic transmission were found to consume about 0.78 mL/km more fuel than vehicles with manual transmission.

Climatic Effects

Studies conducted in temperate countries have shown that seasonal variations of ambient temperature affect fuel consumption rates of vehicles (*6,11,14*). Wet road surfaces on rainy days or in winter are also known to lead to higher fuel consumption because of increased rolling resistance (*6,15*). In the present study, average daily temperature and rainfall were computed for each survey cycle of each participant from daily climatic records provided by the Meteorological Service of Singapore. Correlation analyses of the survey data indicated that the temperature and rainfall variables were highly correlated. Either of the two variables would therefore be adequate to represent the climatic conditions of Singapore. The effect of either temperature or rainfall, when included in the model of Equation 23, was found to be insignificant at a confidence level of 95 percent. This is not surprising because a uniform climate prevails throughout the Singapore island during the whole year. Figure 4 shows the mean monthly variations of temperature and rainfall based on meteorological data collected over 20 years. This finding suggests that no seasonal correction factors are needed for the fuel consumption models derived in this study.

CONCLUSIONS

The analyses performed in this study indicate that the average-speed fuel consumption model (i.e., Equation 8 and Equation 9) applicable to the general automobile traffic in Singapore is comparable to those developed elsewhere for small cars. This finding is consistent with the predominantly small engine capacity of the car population of Singapore. The relationship established is region-specific. It is applicable to the traffic flow, road network layout, driver behavior, and road pavement and climatic conditions in Singapore. This aggregate fuel consumption model is useful for evaluating the energy impact of transportation policies or measures that affect automobile ownership and use.

The survey data also allow the effects of vehicle-specific parameters and climatic conditions to be evaluated. This was achieved by extending the basic average-speed model to include variables representing the parameters of interest. Statistical analyses showed that, in addition to the average traveling speed, factors that had significant impacts on fuel consumption included vehicle weight, engine capacity, vehicle age, and total accumulated odometer mileage, as well as whether the vehicle was equipped with power steering and automatic transmission. Seasonal variations of climatic conditions in Singapore were found to be too small to have any significant effect on fuel consumption rates.

The test results have shown that the survey approach adopted in this study can be used to calibrate the basic average-speed fuel consumption model. In addition, the survey data could be used effectively to identify the effects of various factors on fuel consumption. This approach is cost-effective, and it provides a comprehensive picture of vehicle fuel consumption in actual traffic conditions. A survey of this nature can be conducted easily by any highway agency without having to resort to special measuring equipment. However, this approach cannot be used to study the effects of some factors at the microscopic level, such as speed changes, driver behavior, road geometry, and pavement surface quality.

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