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Driver Behavior Effects on Fuel Consumption in Urban Driving

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Data are examined from two published experimental studies in which drivers were instructed to drive other than normally, with the traffic: for example, to minimize fuel consumption or to minimize trip time. It is found that, in general, for each 1% increase (decrease) in trip time compared to driving normally with the traffic, the fuel consumption increases (decreases) by approximately 1.1%. However, expert drivers can save fuel without increasing trip time by skillfully adjusting their speed to avoid stops at traffic signals. It is shown that the formal problem to be solved to minimize fuel consumption on an urban trip is so complicated that even a "perfect" fuel economy meter would not enable a driver to achieve this minimum.

INTRODUCTION

There has been a great deal of discussion in recent years on various ways to conserve energy. While much of the thrust has been on different technology, changes in human behavior and habits have also been stressed (e.g., lowering home and office thermostat settings and car pooling). Here the question of how changes in driver behavior affect fuel consumption in urban driving is addressed. Although there has been much exhortation in the popular media on this subject, much of the advice is based on "expert opinion" rather than on the results of specific tests. In this paper the results of published experiments in which drivers did alter their behavior will be discussed. It will be shown that these results may be organized into a reasonably consistent pattern.

All the material in this paper relates to urban and suburban driving in which traveling at constant speeds for extended periods does not normally occur. The fuel consumption of a given vehicle in such traffic, which will be called "urban" traffic, is determined by the complex interaction of many factors. These include the detailed control inputs the individual driver makes to his vehicle and how the driver is influenced by interactions with neighboring vehicles and with a complex traffic control system. It is as a consequence of these factors that vehicles embedded in urban traffic undergo frequent changes in speed. Fuel consumption is affected by the manner in which individual and collective human behavior interact with a large complex system, as well as by the physical characteristics of the vehicles.

The urban situation is to be contrasted to that of freeway driving, for which speeds are relatively constant. The fuel consumption at a given constant speed is essentially independent of driver, unless some idiosyncratic behavior, such as "fluttering" the gas pedal, occurs. Fuel consumption for the freeway case is, therefore, determined mainly by purely physical factors. Of course, measures that influence the speed the driver chooses do affect

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fuel consumption; but essentially as a deterministic function of speed for each vehicle. In addition, freeway driving usually involves speeds higher than that at which the vehicle attains its minimum fuel consumption, usually at approximately 60 km/h, so that increases in average speed generally increase fuel consumption. It is for this reason that the nationwide 55 miles per hour (89 km/h) speed limit was introduced. A number of authors have studied the degree to which drivers have obeyed this limit. (See, e.g., Lam and Wasielewski, 1976.) In the urban case, speeds are usually lower than that at which the vehicle attains its minimum fuel consumption, so an increase in average speed would be expected to reduce fuel consumption. Before discussing how changes from "normal" driving can affect fuel consumption in urban driving, certain basic results, obtained for the case of driving "normally, with the traffic" in urban traffic, are reviewed.

FUEL CONSUMPTION WHEN DRIVING NORMALLY IN URBAN TRAFFIC

From data collected by driving instrumented vehicles in actual urban traffic, Evans, Herman, and Lam (1976a; 1976b) and Chang, Evans, Herman, and Wasielewski (1976a; 1976b) showed that the average fuel consumed per unit distance of travel, $\bar{\phi}$, could be expressed as a linear function of the time taken to travel unit distance, $\bar{t}$; that is

$$\bar{\phi} = k_1 + k_2 \bar{t} \qquad (\bar{v} < \sim 60 \text{ km/h}) \quad (1)$$
$$\text{or } 1/\bar{E} = k_1 + k_2/\bar{v}$$

where $\bar{E} = 1/\bar{\phi}$ is the average fuel economy, and the relation applies for trip speeds $\bar{v} = 1/\bar{t}$ less than about 60 km/h. Note that the variables $\bar{t}$, $\bar{v}$, $\bar{\phi}$, and $\bar{E}$ in Equation 1 must not be interpreted as instantaneous values. They are averages over segments of travel (for example, between consecutive stops of the vehicle) that include a variety of speeds. The average trip speed is the total distance of the trip segment divided by the time taken, including stopped time.

The fit of Equation 1 to field data shown in Figure 1 for two vehicles is typical of that for all 11 vehicles so far tested in the field (Evans and Herman, 1978a). No effects dependent on drivers have been observed for different drivers instructed to drive "normally, with the traffic." For example, Figure 2 shows data from Evans, Herman, and Lam (1976b) for four different drivers. The data scatter in an essentially random manner around the common regression line. More detailed regression analyses for each driver in the original paper showed no systematic effects dependent on drivers. Jones and Appleby (1978) also found little difference in the fuel economies of dif-

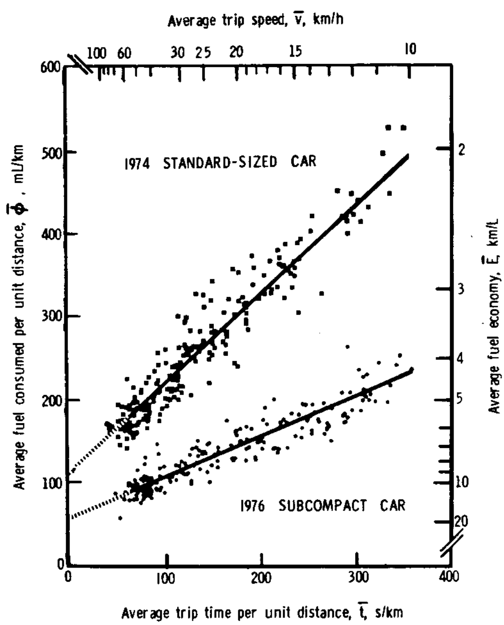

Figure 1. *Examples of the fit of fuel consumption data to Equation 1. Each point is for a segment of travel from the beginning of one stopped period to the beginning of the next stopped period during the course of a long trip which encompassed a variety of traffic conditions. (From Chang, Evans, Herman, and Wasielewski, 1976a, 1976b)*

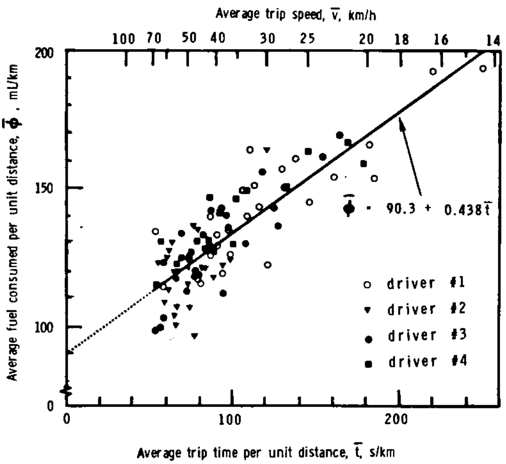

Figure 2. *Average fuel consumed per unit distance versus average trip time per unit distance for four drivers driving the same 1973 subcompact car "normally, with the traffic." (From Evans, Lam, and Herman, 1976b)*

ferent drivers driving normally beyond what could be explained by speed variation.

Given the complexities implicit in urban traffic, it is indeed surprising that so simple a relation as Equation 1 can so adequately describe fuel consumption in such traffic. All the traffic characteristics coalesce into the single quantity, the average trip time per unit distance. When the traffic moves slower (i.e., $\bar{t}$ increases), the vehicles embedded in it use more fuel, as given by Equation 1. The reason that so simple a relation applies can be given in terms of the properties of urban traffic and the physical characteristics of a particular vehicle (Evans, et al., 1976a; 1976b; Chang, et al., 1976b).

Equation 1, which is for normal driving, with the traffic, has been found to describe well urban fuel consumption data from a variety of sources, as discussed by Evans (1978):

Field
(Evans, et al., 1976a; 1976b; Chang, et al., 1976b; Chang, Evans, Herman, and Wasielewski, 1977a; Evans and Herman, 1978a; Srinivasan, Shetty, and Rao, 1975; Everall, 1968; Pelansky, Blunden, and Munro, 1968; and Roth, 1959)

Detailed Computer Simulation
(Chang, Evans, Herman, and Wasielewski, 1977b; Evans and Herman, 1978b)

Same Vehicle on Different Fixed Urban Driving Schedules
(Evans and Herman, 1978a)

Small Segments of One Fixed Urban Driving Schedule
(Evans, 1979)

Equation 1 effectively describes how fuel consumption in urban traffic depends on traffic conditions when drivers drive "normally, with the traffic." The results of some experiments in which drivers were instructed to drive other than normally are now considered.

INSTRUCTIONS TO CHANGE DRIVER BEHAVIOR

Chang, et al. (1976a; 1976b) conducted tests in which a total of 34 trips were made by nine different drivers following various driving instructions over a fixed route of 27 km in suburban Detroit. The same vehicle, a 1974 standard-sized car with automatic transmission, 6.6 L displacement V-8 engine and 2259 kg test mass was used for all the tests.

The choice of drivers and the set of instructions were designed to produce a relatively wide range of fuel consumption. The nine drivers included one with considerable experience in driving to minimize fuel consumption and others knowledgeable in the field. The magnitudes of effects measured are not necessarily typical of any other group of drivers but are useful in indicating relations between variables as well as extremes of fuel consumption and trip time that might be found on this route. Some sets of instructions involved the use of a vacuum gauge fuel economy meter with a dial divided into three color regions: green indicated good fuel economy, while orange and red indicated high power with correspondingly reduced fuel economy. Seven different instructions were used:

(1) Drive normally with the traffic
(2) Minimize trip time
(3) Use vigorous acceleration and deceleration
(4) Minimize fuel consumption
(5) Maintain fuel economy meter in green region
(6) Maintain fuel economy meter in green or orange region
(7) Drive like a hypothetical very cautious driver.

For Instruction 2, drivers generally used vigorous acceleration up to an appropriate speed for the route, changed lanes freely, and adjusted their speed so as to pass through traffic lights "on the fly" when possible. For Instruction 3, drivers attempted to maintain the maximum appropriate speed whenever possible. They did not use foresight to anticipate situations in which a temporary speed reduction might lead to a reduced total trip time, as under Instruction 2. The driver responses to Instruction 4 can be classified into two groups. In some cases, drivers responded mainly by reducing acceleration and speed. In other cases drivers reduced the number of stops through appropriate speed adjustments, using rather high accelerations in some instances. These two groups are referred to as 4a and 4b, respectively. The instruction to maintain the economy meter in the green region could only be carried out by limiting accelerations to much lower values than ordinarily occur in traffic. Keeping the meter in the orange region also required rather low accelerations, but did not require limiting accelerations to values below those normally used in traffic. For Instruction 7, drivers used low acceleration and speed and avoided lane changes.

When drivers alter their driving strategy, data for segments of travel between consecutive stops no longer scatter randomly around the regression line, Equation 1, for the particular car. This is shown in Figure 3 which shows values of $\bar{\phi}$ and $\bar{t}$ for segments of travel between consecutive stops for one typical run under Instruction 2 and one typical run under Instruction 4 by the same driver. The line is

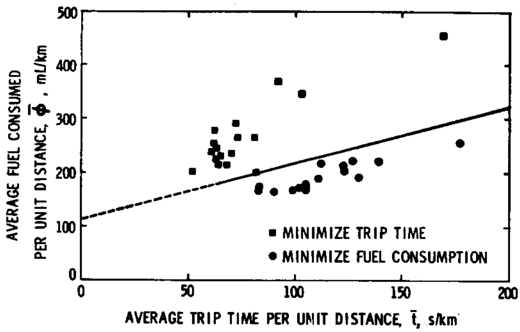

Figure 3. *Average fuel consumed per unit distance versus average trip time per unit distance for segments of travel between consecutive stops for trips made under Instruction 2 (minimize trip time) and Instruction 4 (minimize fuel consumption). The straight line is the same Equation 1 fit to data for "normal" driving shown in Figure 1 for the 1974 standard-sized car. (From Chang, Evans, Herman, and Wasielewski, 1976a)*

Equation 1 for the test vehicle when driving normally with the traffic. Note not only the systematic departures from the linear relation, but also that the average values of $\bar{t}$ and $\bar{\phi}$, which relate to the overall values for the trip are different for the two instructions.

The average values of trip times and fuel consumption for all seven instructions, as reported in Chang, et al., 1976a, are given in Table 1 and plotted on a fuel consumption versus trip time diagram in Figure 4. These points do not fit the regression line, Equation 1, derived for this car (Chang, et al., 1976a; 1976b), which is also shown in Figure 3. In fact, a line fitted to these points, except for Instruction 5, would be approximately orthogonal to the regression line.

These results illustrate the contrast between the effect of speed changes due to traffic conditions and speed changes due to altered driving patterns in a given traffic situation. Drivers who drive with the traffic experience lower fuel consumption when their mean speed increases, owing to an increase in the speed of the traffic stream. However, drivers who increase their speed above that of

TABLE 1

Effect of Different Driving Instructions on Fuel Consumption and Trip Time (Data from Chang, Evans, Herman, and Wasielewski, 1976a, for 2559 kg car)

Instruction	Number of Trips	Average Trip Time, $\bar{t}$, s/km			Average Fuel Consumption, $\bar{\phi}$, mL/km		
		Mean	Standard Deviation	% Different from "Normal"*	Mean	Standard Deviation	% Different from "Normal"*
1	11	89.1	7.1	—	202	6	—
2	6	77.0	4.7	−13.6	222	15	9.9
3	3	79.6	6.0	−10.7	237	16	17.3
4	8	89.6	6.6	(0.6)	181	13	(−10.4)
5	1	118.0	—	(32.4)	206	—	(2.0)
6	2	90.4	5.9	1.5	191	5	−5.4
7	3	96.0	10.6	7.7	188	9	−6.9
4a	4	93.0	8.2	4.4	189	15	−6.4
4b	4	86.3	1.5	(−3.1)	174	5	(−13.9)

* Instruction No. 1.

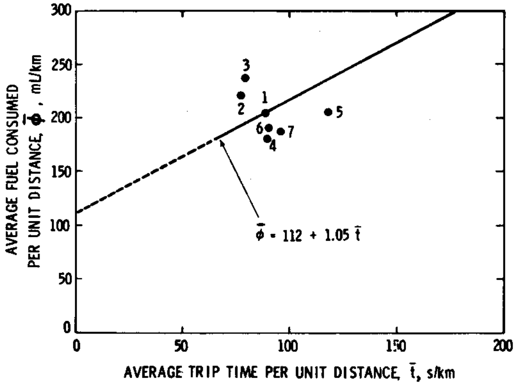

Figure 4. *Average fuel consumed per unit distance versus average trip time per unit distance for trips under various driver instructions. Note that the averages here are for a 27 km trip, and not the small segments of travel used in the earlier figures. The numbers correspond to the list of driver instructions given in the text. The straight line is the same as that shown in Figures 1 and 2. (From Chang, Evans, Herman, and Wasielewski, 1976a, 1976b)*

the traffic stream save time but experience higher fuel consumption. Drivers who reduce their mean speed below that of the traffic stream may save fuel, although the very low accelerations required by Instruction 5 result in increased fuel consumption as well as increased trip time.

Drivers generally achieved lower fuel consumption under Instruction 4 which permitted speed adjustments to avoid stops, than under Instructions 5, 6, and 7, which involved reduced accelerations but did not generally permit effective speed adjustments to avoid stops. Indeed, the average trip time under Instruction 4 for drivers who reduced the number of stops was lower than for most "normal" runs. This is easy to understand when one considers the fuel penalty imposed by a stop at a red light. Measurements for the test car, which are consistent with the results of Claffey (1971) show that a driver who stops, idles for 30 s while waiting for the light to change, and accelerates to resume a speed of 60 km/h uses approximately 70 mL more fuel than a driver who passes through the signal at a constant speed of 60 km/h. The test route used involved passing through 56 traffic signals.

In a series of tests conducted in Britain using two cars with manual transmissions, Everall (1968) used the following driving instructions:

(a) Drive as economically as possible
(b) Drive as you would normally
(c) Drive as if you were in a hurry

The information presented in Table 2 was generated from the results plotted in Figure 4 of Everall (1968). The percentage change in fuel consumption versus the percentage change in trip time is plotted in Figure 5 for the data in Table 2 and most of the data in Table 1. The data from Table 1 not plotted are: Instruction 5—maintain fuel economy meter in green region; and 4b—data for the drivers who saved fuel by skillfully "playing" the lights. Both of these represent types of driving that ordinary, unaided drivers would probably be unable or unwilling to produce. The results for these two cases do not fit the pattern of Figure 5.

The remaining data that are plotted in Figure 4 yield a fairly orderly pattern. A least squares fit to the 9 data in Figure 5 yields the result

$$\text{percentage change in } \bar{\phi} = -1.08 \times \text{percentage change in } \bar{t}. \qquad (2)$$

Note that the regression passes through the origin because the quantities plotted are deviations from average values. When a driver alters behavior to change trip time by $x\%$, fuel consumption changes by $-1.1\,x\%$. Note that the data in Figure 5 give no suggestion of any asymmetry between the effect of increasing (i.e., $x > 0$) or decreasing (i.e., $x < 0$) trip time.

If a driver drives normally with urban traffic, then the fuel consumption is given by Equation 1. If trip times decrease due to decreased congestion, then fuel consumption will also decrease. However, if the traffic remains the same, and the driver decreases trip time by driving faster than the traffic, more—not less—fuel will be used.

It is interesting to note that, although the two different cars used by Everall (1968) yielded rather different results in response to changes in driver instruction, the data, nonetheless, lie along the same line (see Figure 5).

The results in Figure 5 suggest that by reducing acceleration levels and generally driving more "gently," a driver can reduce fuel consumption by as much as about 15%, but at the expense of increasing trip time by

TABLE 2

Effect of Driver Instruction on Trip Time and Fuel Consumption (Data from Everall, 1968)

				% Difference from Instruction b (drive normally)	
*Vehicle**	*Instruction*	$\bar{t}$, s/km	$\bar{\phi}$, mL/km	$\bar{t}$	$\bar{\phi}$
Large Saloon	a(save fuel)	77.6	107	6.9	−9.3
Test mass: 1478 kg	b(normal)	72.6	118	—	—
1.7 L Displacement	c(save time)	69.8	123	−3.9	4.2
Small Saloon	a(save fuel)	80.9	74	12.7	−12.9
Test mass: 1021 kg	b(normal)	71.8	85	—	—
1.06 L Displacement	c(save time)	65.3	93	−9.1	9.4

* Both vehicles had manual transmissions and four cylinder engines.

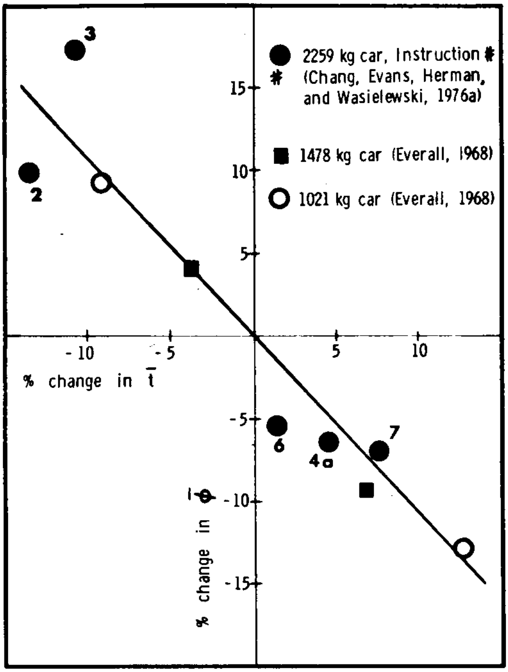

Figure 5. *The percentage change in fuel consumption versus the percentage change in trip time for data given in Tables 1 and 2.*

approximately 15%. Similarly, a driver can reduce trip time by as much as about 15%, but at the expense of increasing fuel consumption by approximately 15%. Note that case 4b from Table 1 is excluded from the above discussion. For that case, a 14% reduction in fuel consumption was achieved without increasing trip time by skillfully avoiding stops.

All the above results were for traffic moving at average speeds of 40 km/h to 50 km/h. When traffic becomes more free-flowing, say at approximately 60 km/h, the possibilities of saving fuel or time (subject to compliance with speed limits) would appear to diminish. Similarly, when approaching traffic jam conditions (i.e., very low speeds), the opportunities for a driver to alter behavior to save time or fuel also become more limited. These qualitative features suggest a representation of the type shown in Figure 6, in which the

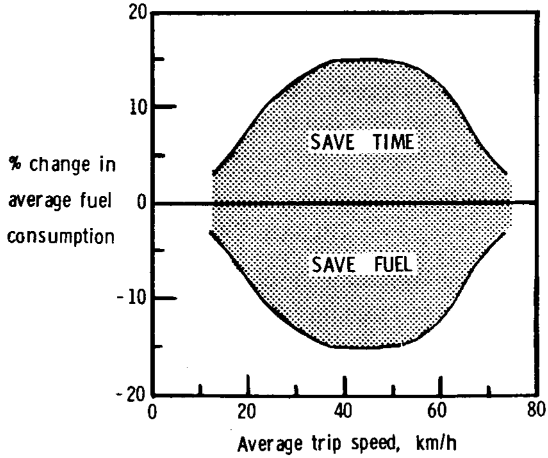

Figure 6. *Sketch of plausible region over which an unaided driver with no particular expertise at fuel saving might vary his behavior to save fuel or time.*

shaded area indicates the range over which an untrained driver may realistically vary behavior. In the absence of specific experimental results, the curves in Figure 6 are presented to indicate plausible qualitative features. The picture will become clearer only after additional experimental studies have been performed.

EFFECTIVENESS OF FUEL ECONOMY GAUGES

The 5% reduction in fuel consumption for the instruction to keep the fuel economy meter in the orange and green region (Instruction 6) may be contrasted to reductions of 10% and 7% for the unaided Instructions 4 and 7 (see Table 1). When the meter was kept in the green region (Instruction 5), trip time increased considerably, but with no corresponding reduction in fuel consumption. Banowetz and Bintz (1977) compared the fuel economies of 70 vehicles equipped with fuel economy meters to those of 70 control vehicles not so equipped. The fuel economy meter displayed the (essentially) instantaneous miles per gallon. The drivers of all 140 vehicles were motivated to save fuel. The vehicles were used for 12 weeks of normal driving. The meter-equipped vehicles had fuel consumption, on average, approximately 3% less than the nonequipped vehicles, though the authors report that they did not find this difference to be statistically significant.

MINIMIZING FUEL CONSUMED ON AN URBAN TRIP

Some reasons why fuel economy gauges do not lead to large fuel savings in urban driving are implicit in the task of minimizing fuel consumption in an urban trip. Consider a vehicle equipped with a perfectly accurate instantaneous fuel economy meter. A driver could readily use such a meter to reduce fuel consumption on a long constant speed trip by "hunting" for the constant speed that maximized fuel economy. However, as noted earlier, urban driving is characterized by the absence of constant speeds. Given that the vehicle must stop at traffic lights, slow down for traffic, etc., how should the driver respond to the fuel economy meter? Clearly, an attempt to always have high instantaneous fuel economy will not produce the desired result. The instantaneous fuel economy always increases when the accelerator is released and always decreases when it is depressed. An attempt to produce the highest possible fuel economy at each instant will soon bring the vehicle to a stop (or creep), with an overall trip fuel economy of zero (or near zero). If the driver does not strive for instantaneous maximum fuel economy, then what goal should be pursued? Suppose the driver knew all the information pertinent to a given trip, and had unlimited computational capabilities, then what problem needs to be solved?

Assume that the driver has to execute an urban trip of distance D, and wishes, with the aid of a perfect fuel economy meter, to choose speed as a function of time to minimize total fuel consumption.

The total fuel consumed on the trip, F, is given by

$$F = \int_0^D dF = \int_0^D \frac{dF}{dx}\, dx = \int_0^D \frac{dx}{E} \qquad (3)$$

where E is the instantaneous fuel economy, and an amount of fuel, dF, is used to travel distance dx. Equation 3 can be cast in the time domain rather than the spatial domain, by writing

$$F = \int_0^{T(D)} \frac{v}{E}\, dt \qquad (4)$$

where $v = dx/dt$ is the instantaneous speed, and T is the total trip time.

Note that at zero speed, the fuel economy is zero. However, the ratio v/E at zero speed is *not* zero, because

$$\left(\frac{v}{E}\right)_{(v=0)} = \left(\frac{dx}{dt} \cdot \frac{dF}{dx}\right)_{(v=0)} = \left(\frac{dF}{dt}\right)_{(v=0)} \qquad (5)$$

where the quantity on the right-hand side of Equation 5 is the idle fuel flow rate. It has been previously shown (Evans, et al., 1976a; 1976b; Chang, et al., 1976a) that the idle fuel flow rate is of great importance in determining urban fuel consumption. Even a hypothetically "perfect" fuel economy meter yields no information on the idle fuel flow rate, because it registers zero when the vehicle is stopped.

If one were given the idle fuel flow rate, and E as a function of speed and acceleration, and a complete description of the location and phases of traffic signals, and trajectories of all other vehicles, it would probably be possible to derive, with the aid of a computer, a driver strategy (i.e., v as a function of time) that would minimize F in Equation 4. Clearly, a driver cannot possibly solve such a problem in real time while driving. In any event, real-world boundary conditions are continuously changing in unpredictable ways.

Given that one cannot provide an optimum strategy for use of a fuel economy meter, what can one advise a driver regarding fuel saving in urban traffic? The following three actions are suggested to be of prime importance in reducing fuel consumption in urban traffic.

(1) Anticipate conditions ahead so that braking is minimized. Do not accelerate to a higher speed than required if you must later slow down or stop. Every time the brakes are applied, energy previously extracted from the fuel is unproductively dissipated.
(2) Avoid stopped delays. Fuel used idling when the vehicle is stopped is of great importance in urban driving. Also, after the stop, the lost kinetic energy must be restored. It has been estimated that a driver who stops, idles for 30 s while waiting for a light to change, and accelerates to resume a speed of 60 km/h uses about 70 mL more fuel than a driver who passes through the signal at a constant speed of 60 km/h.
(3) Use low acceleration levels, unless a higher level will contribute to achieving actions 1 or 2, as in, for example, accelerating briskly up to the speed limit to make a traffic light.

Instantaneous fuel economy gauges relate only to action number 3, because they indicate low fuel economy for large accelerations. Such meters might effectively remind drivers of the fuel saving associated with low accelerations, and further motivate them to be conscious of the whole question of fuel saving.

Considerations of the benefits of vacuum fuel gauges or other fuel economy meters as engine diagnostic tools which can indicate fuel uneconomic engine conditions are beyond the scope of the present paper.

POSSIBLE EFFECT ON OVERALL TRAFFIC SYSTEM

The information in Figure 5 shows that it is possible for drivers to save fuel in urban traffic by simply driving more gently. Such a change also increases trip time. More effective strategies are possible, in which fuel may be saved without increasing trip time, if the driver can anticipate traffic signals and avoid stops.

All the information presented in this paper relates to the driver's behavioral change in existing traffic. If all drivers changed their behavior, then the collective characteristics of the traffic would change. Unfortunately, no data are available on this extremely important aspect of the problem. If the queue leader at a red traffic signal chooses a low, fuel economic, acceleration when the light turns green, that driver will save fuel. However, when the signal is overloaded, this action might reduce the throughput of the signal, leading to increased average trip times in the system. If this occurs it will lead to increased system fuel consumption (Evans and Herman, 1976). It is, unfortunately, not known how these various factors would balance out in practice. However, the possibility exists that if everyone adopted "effective" individual fuel saving strategies, the net result might be an increase in the fuel consumption for the average user.

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