

Gasoline Consumption in Urban Traffic

Man-Feng Chang, Leonard Evans, Robert Herman, and Paul Wasielewski,
General Motors Research Laboratories

A linear relation between fuel consumption per unit distance ϕ and trip time per unit distance \bar{t} , $\phi = k_1 + k_2\bar{t}$, has been shown to adequately explain fuel consumption for different drivers driving normally in urban traffic. In the present study, the applicability of this relation to a wider range of drivers, traffic, driver motivations, ambient temperatures, and vehicles is experimentally investigated. The effect of different driver instructions is studied. For example, drivers instructed to minimize trip time experienced higher fuel consumption than predicted by the linear relation, while those who drove slower than the traffic generally consumed less fuel. The parameters k_1 and k_2 obtained for different vehicles are approximately proportional to vehicle mass and idle fuel flow rate respectively; therefore, fuel consumption in urban traffic can be predicted from easily measurable vehicle characteristics. The excess fuel consumed because of cold starts is determined as a function of trip length for different ambient temperatures. These data are combined with data on the dependence of commuting trip speed on trip length to show that the fuel consumed in commuting trips increases substantially less rapidly than trip distance.

Recent investigations (1, 2) and a number of earlier studies (3, 4, 5) show that the gasoline consumed per unit distance in urban driving at speeds less than ~ 60 km/h can be expressed as a linear function of the average trip time per unit distance:

$$\phi = k_1 + k_2\bar{t} \quad \bar{v} < \sim 60 \quad (1)$$

where

ϕ = fuel consumed per unit distance,
 \bar{t} = average trip time per unit distance (i.e.,
the reciprocal of the average speed \bar{v}), and
 k_1 and k_2 = constants.

It is surprising that a process as complex as fuel consumption in urban driving, which depends on many factors such as speed changes, braking, and stopped delays, can nevertheless be described by so simple an expression. Part of the explanation is that the other

relevant traffic variables are themselves correlated with the reciprocal of the average speed. Equation 1 organizes a large quantity of complex data. This paper investigates the adequacy of this equation in describing fuel consumption in urban driving in which a wider range of drivers, traffic, driver motivations, ambient temperature, and vehicles are considered than in the previous study (1, 2).

As a consequence of equation 1, the total fuel consumed, F , in a trip of distance D and duration T is given simply by

$$F = k_1D + k_2T \quad (2)$$

After equation 2 has been calibrated for a particular vehicle in urban traffic, fuel consumption for particular trips can be estimated by merely noting the distance and duration of the trip, for which a watch and odometer are sufficient instrumentation. In the present study, equation 2 is applied to trips made by a number of different drivers in a variety of traffic situations to further test its generality.

Fuel consumption studies conducted in Britain showed differences between different drivers driving normally (3). Still larger differences were observed when drivers were instructed to drive economically or as if in a hurry (4). Our investigations (2) did not reveal differences among four drivers driving normally with the traffic. This study further investigates the effect of different drivers and of instructions to drive differently from normal. In particular, data for drivers attempting to conserve fuel or save time are analyzed.

The quantities k_1 and k_2 have been interpreted in terms of a model of the engine-vehicle system that relates them to easily measurable vehicle characteristics. Values of k_1 and k_2 have been obtained for different vehicles to investigate this interpretation.

The discussion so far has presumed a fully warmed vehicle. However, about one-third of all distance driven is for trips to and from work (6). In such commuting trips the vehicle starts cold and may not be fully warmed up even when it arrives at its destination.

Analyses of the excess fuel consumed in cold starts have generally been based on observations of fuel con-

sumption over prescribed driving cycles (7,8). In the present study, observations of fuel consumption in actual traffic are used to obtain quantitative estimates of modifications that must be made to equations 1 and 2 in the case of a cold start. Estimates of fuel consumed in commuting trips are also given as a function of the distance of the commuting trip, taking into account that the average speed of a commuting trip tends to be a function of the distance of the trip (9,10). The effect of ambient temperature is also considered.

EXPERIMENTAL DETAILS

Equipment

Fuel consumption was measured by using a model 74 fuel meter developed by General Motors. The transducer of this instrument generates an electronic pulse for each 1.0 ml of gasoline delivered to the vehicle carburetor. A digital display mounted in the passenger compartment shows the accumulated number of ml of fuel, elapsed time to 0.1-s resolution, and fuel temperature to 1°C.

Distance was measured by reading the vehicle's odometer, which was calibrated. By interpolating between the 0.16-km digits, odometer measurements with a standard deviation of 0.014 km were obtained. Inasmuch as distances involve differences between consecutive odometer readings, the standard deviation of a distance measurement is accordingly 0.020 km.

A 1974 standard-sized passenger car with a 6600-cm³ displacement V-8 engine, two-barrel carburetor, and three-speed automatic transmission was the primary test car and was used for all experiments except calibration of equation 1 for different cars. Its mass, including test equipment and a typical driver, was 2259 kg. Details of the other vehicles used are given later.

All fuel measurements were reduced to standard conditions of ambient temperature and fuel temperature in accordance with the recommended practice of the Society of Automotive Engineers (11). A small correction was also made to account for additional weight for trips with more than one occupant.

Method

The basic approach was to measure the fuel consumed, distance traveled, and time taken for each of a number of small sections of travel that together composed a trip. These data could then be interpreted in terms of equation 1. It has been shown (2) that the results of such analyses are relatively unaffected by the choice of any one of four methods of dividing the trip data into smaller sections. Consequently, the most convenient of these sampling methods was adopted, namely recording data at each stop. A section of travel between consecutive stops is called a microtrip. A normal trip starting and terminating at a specific location is called a macrotrip.

Using microtrips as data elements has a number of advantages. The net acceleration in a portion of a trip has a significant effect on its fuel consumption (2). The net acceleration of all microtrips is zero, so that the effect due to this variable does not contribute any additional variance to the results. An observer can more reliably read synchronous values of fuel consumed, distance traveled, and elapsed time with the vehicle stopped.

Much of the data were collected by unassisted drivers who orally recorded the cumulative fuel consumed, distance traveled, and elapsed time on a portable tape recorder. In some cases, such as when the effect of different driving patterns was investigated, an accompanying observer recorded the data.

For warm start trips, the vehicle was driven around for about 20 min before data collection began. For cold starts, the vehicle was parked outdoors for at least 8 h prior to data collection and was idled for 30 s before it was moved, as recommended by the manufacturer. In practice, some departures from this procedure occurred. The vehicle's fuel tank was normally maintained at above three-quarters full.

All data were collected on essentially level roads within 40 km of General Motors Technical Center, Warren, Michigan, from November 1974 to July 1975. Nine male General Motors employees, including the authors, served as drivers.

RESULTS

Relation Between ϕ and \bar{t}

For an appropriate data base to calibrate equation 1, two long trips were made over a route designed to include a wide variety of traffic conditions. The roadways are major urban arterials, business streets in the Detroit CBD, and local streets in Mount Clemens, a town of 21 000 population situated 34 km from Detroit. The values of ϕ and \bar{t} for the 206 microtrips making up the long trip are shown in Figure 1. The straight line is a fit to the data for $65 \text{ s/km} < \bar{t} < 365 \text{ s/km}$. The curves represent constant-speed fuel consumption per unit distance.

Differences in the character of the traffic on the three types of roadway are apparent from the distributions of average trip time per unit distance for the corresponding microtrips. However, all three groups of microtrips lie close to the same regression line, indicating that equation 1 can be applied to varied roadway situations.

To avoid large percentage errors in distance measurement due to the 0.020-km distance measuring resolution, microtrips shorter than 0.2 km are consolidated with the preceding microtrip. Microtrips with $\bar{t} < 65 \text{ s/km}$ ($\bar{v} > 55 \text{ km/h}$) are not included in the analysis inasmuch as equation 1 is not expected to apply to such high speeds (fuel consumption increases with speed). The remaining points are not evenly distributed over the range of \bar{t} but instead are concentrated at lower values of \bar{t} . To avoid giving undue weight to the data in this range, we adopted Everall's procedure (4). The data were grouped into intervals of 10 s/km in \bar{t} , and the regression was based on the average values of ϕ and \bar{t} in each interval in the range $65 \text{ s/km} < \bar{t} < 365 \text{ s/km}$. The upper limit is the largest value of \bar{t} for which a useful number of data were available.

The resulting linear regression obtained for the primary test car is

$$\phi = 112 + 1.05\bar{t} \quad (3)$$

where ϕ is in ml/km and \bar{t} in s/km. This line is shown in Figure 1. Also shown in Figure 1 is the constant-speed fuel consumption in different transmission gears. The data plotted were made available to us by General Motors engineering staff and were computed by their GPSIM procedure (12). Our test track measurements of constant-speed fuel consumption are in good agreement with these data.

Prediction of Fuel Consumption for Macrotrips

Although equation 3 was derived by analyzing microtrips, it can be converted, as was discussed earlier, into an equation for the total fuel consumed, F , in a trip of arbitrary distance D completed in time T to give

$$F = 112D + 1.05T \quad (4)$$

where T is in seconds, D in kilometers, and F in milliliters.

A total of 26 macrotrips with distances ranging from 8 to 36 km were driven by nine drivers instructed to drive normally and to keep up with the traffic. Many of these macrotrips were obtained in connection with other parts of the study.

The actual fuel consumed in the macrotrips was compared with that predicted by equation 4. The predicted differed from the observed by -6.3 to 9.3 percent, with a root mean square value of 3.8 percent. This result indicates that most of the variability in fuel consumption per unit distance depends on the average trip time per unit distance, irrespective of the individual driver. This is in agreement with our findings (2) but contrasts with Roth's results (3), in which the fuel consumption of five different drivers driving at the same average trip speed varied about 20 percent. This difference may be attributable to the fact that the vehicles used in Roth's research (3) had manual transmissions, and the vehicles used here and in an earlier study (1, 2) had automatic transmissions.

Our results indicate that equation 4 provides acceptable predictions of fuel consumed on a trip of distance D and time T , relatively independent of roadway type, traffic conditions, or driver.

Physical Interpretation of Parameters k_1 and k_2

It has been pointed out (1, 2) that the linear relation between ϕ and \bar{t} can be interpreted in terms of a model of the engine-vehicle system developed by Amann, Haverdink, and Young (13). The parameter k_1 is the fuel consumed per unit distance to overcome rolling resistance. Because the rolling resistance is approximately proportional to the mass of the vehicle for similar types of vehicles, we would expect k_1 to be approximately proportional to vehicle mass.

The parameter k_2 is the fuel consumed per unit time to overcome various mechanical losses. This fuel does not directly produce tractive power and may be considered to be approximately represented by the idle fuel flow rate. In the limit of zero speed, k_2 is the idle fuel flow rate (2). We would accordingly expect k_2 to be approximately proportional to the idle fuel flow rate.

To test these physical interpretations of the parameters k_1 and k_2 , equation 1 has been calibrated for a number of different cars. The resulting linear equations for all the vehicles tested, including one from earlier research (2), are shown in Figure 2. In all cases, the percentage of variance explained by the linear relation was similar. The values of the parameters k_1 and k_2 for the curves in Figure 2, as well as other characteristics of the cars, are given in Table 1. Data given in (or computed from) other sources (3, 4, 5) are also presented in this table.

Figure 3 shows k_1 plotted versus the vehicle mass, and Figure 4 shows k_2 plotted versus the directly measured idle fuel flow rate for all available data. These figures show that k_1 is approximately proportional to vehicle mass and k_2 is approximately proportional to idle fuel flow rate.

For large values of \bar{t} , the slope of the line for fuel consumption per unit distance versus trip time per unit distance becomes identical to the idle fuel flow rate when stationary (1). However, the constant of proportionality between k_2 and the idle fuel flow rate is 1.21 for our data (Figure 4). Hence, for sufficiently large values of \bar{t} , the slopes of curves such as those in Figure 2 will approach

values lower than the plotted slopes, which were determined from actual urban traffic data in the range $65 < \bar{t} < 365$ s/km.

From the vehicle mass and idle fuel flow rate, an approximate expression in the form of equation 1 can be derived for fuel consumption in urban traffic by using the relations in Figures 3 and 4.

Different Driver Instructions

The fuel consumption of different drivers driving normally with the traffic is well explained by equations 3 and 4. Deviations from this formula might be expected when drivers alter their normal behavior to save time or to conserve fuel (4). To study this aspect of fuel consumption, 34 test runs were made by nine drivers following various driving instructions over a fixed route of 27 km in suburban Detroit.

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. The results obtained were not expected to be typical of any group of drivers but should be useful in indicating the 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 for good fuel economy and orange and red for high power with correspondingly reduced fuel economy. Seven instructions were given:

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, and
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 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: those who responded mainly by reducing acceleration and speed and those who reduced the number of stops through appropriate speed adjustments, by using rather high accelerations in some instances. The instruction to maintain the economy meter in the green could only be achieved by limiting accelerations to values much lower than those that ordinarily occur in traffic. Keeping the meter in the orange also required rather low accelerations, but they did not seem outside the range of those normally used in traffic. For instruction 7, drivers used low acceleration and speed and avoided lane changes.

The average values and standard deviations of the fuel consumption and trip times for the different instructions are given in Table 2; the average values are shown in Figure 5. These points do not fit the regression line (equation 3) obtained from the microtrips. In fact, a line fit to these points, except for instruction 5, would be approximately orthogonal to the regression line. These results illustrate the contrast between speed changes due to traffic conditions and speed changes due to altered driving patterns in a given traffic situation.

Drivers driving with the traffic experience better fuel economy when their mean speed increases because of an increase in the speed of the traffic stream. However, drivers who increase their speed above that of the traffic stream save time but experience poorer fuel economy. Drivers who reduce their mean speed below that of the traffic stream may save fuel, although the very low accelerations required by instruction 5 resulted in increased fuel consumption as well as increased trip time. Drivers generally achieved better fuel economy under instruction 4, when they were permitted to adjust their speed to avoid stops, than under instructions 5, 6, and 7, when they reduced accelerations but did not generally adjust their speeds 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 we consider the fuel penalty imposed by a stop at a red light. Measurements for our primary test car, which are consistent with Claffey's results (14), 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 about 70 ml more fuel than a driver who passes through the signal at a constant speed of 60 km/h. Our test route included 56 traffic signals.

It is thus possible for drivers to reduce their fuel consumption in urban traffic by adopting effective driving patterns. However, most of these data were for drivers

Figure 1. Average fuel consumption per unit distance versus average trip time per unit distance. The curves represent constant speed fuel consumption per unit distance.

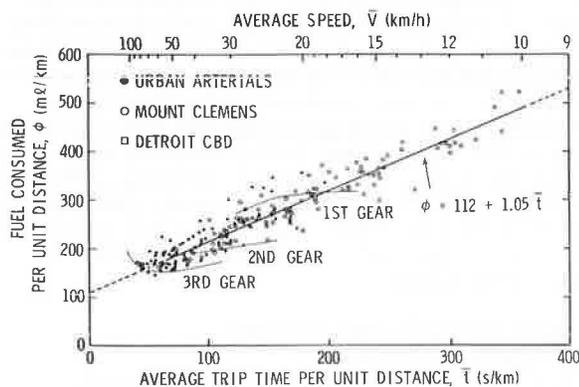


Figure 3. k_1 versus vehicle mass.

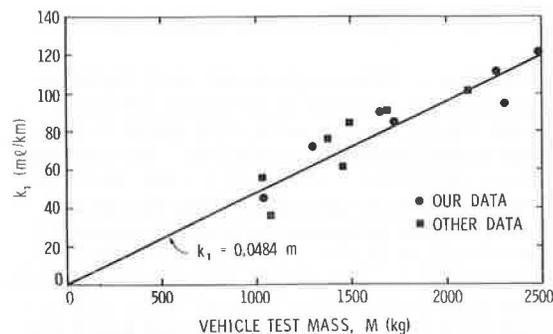


Figure 2. Linear relation $\phi = k_1 + k_2 \bar{t}$ for six vehicles in this study and one vehicle from previous research (2).

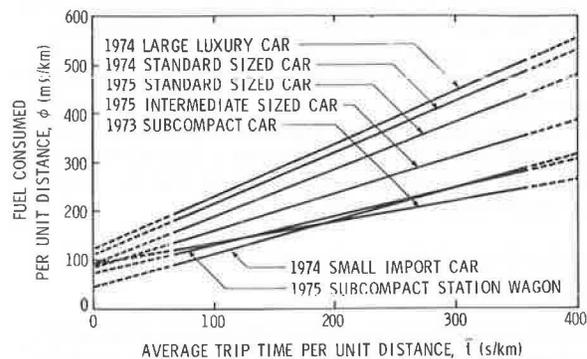


Figure 4. k_2 versus directly measured idle fuel flow rate.

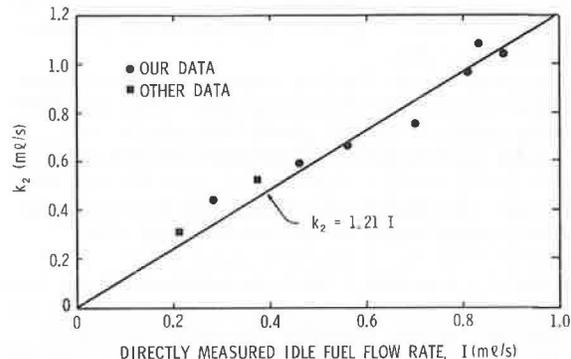


Table 1. Characteristics of vehicles in the present study and earlier research.

Reference	Vehicle	Model Year	Test Mass, M (kg)	k_1 (ml/km)	k_1/M [(ml/km)/kg]	k_2 (ml/s)	Measured Idle Fuel Flow Rate, I (ml/s)	k_2/I
Present study	Standard-sized car	1974	2259	111.59	0.0494	1.045	0.88	1.187
	Standard-sized car	1975	2291	94.64	0.0413	0.964	0.805	1.198
	Small imported car	1974	1033	45.54	0.0441	0.664	0.56	1.186
	Intermediate size car	1975	1720	85.12	0.0495	0.756	0.70	1.080
	Large luxury car	1974	2483	121.80	0.0491	1.084	0.83	1.306
	Subcompact station wagon	1975	1285	72.19	0.0562	0.590	0.46	1.283
	Subcompact car	1973	1642	90.30	0.0550	0.440	0.28	1.571
2	Small van	1956	1067	35.93	0.0337	0.313	0.21	1.490
3	British car	1955	1372	76.83	0.0560	0.523	0.37	1.414
4	Minibus, empty	1965	1686	91.26	0.0541	0.349		
4	Minibus, loaded	1965	2083	100.91	0.0484	0.400		
4	Small British car	1965	1021	56.45	0.0553	0.322		
4	British car	1964	1478	84.91	0.0574	0.532		
5	Australian station wagon	1965	1451	62.10	0.0428	0.595		

Table 2. Effect of driving instructions on fuel consumption for macrotrips.

Instruction	ϕ		\bar{t}		Number of Runs
	Mean	S.D.	Mean	S.D.	
1	202	6	89.1	7.1	11
2	222	15	77.0	4.7	6
3	237	16	79.6	6.0	3
4	181	13	89.6	8	
5	206		118		1
6	191	5	90.4	5.9	2
7	188	9	96.0	10.6	3

Figure 5. Average fuel consumption per unit distance versus average trip time per unit distance for trips under various driver instructions.

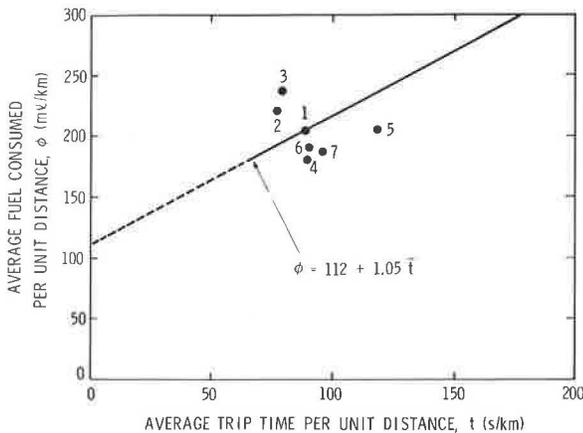


Figure 6. Average excess fuel consumed because of cold start versus distance traveled.

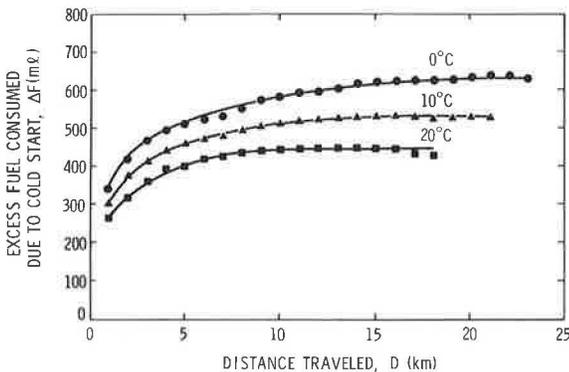
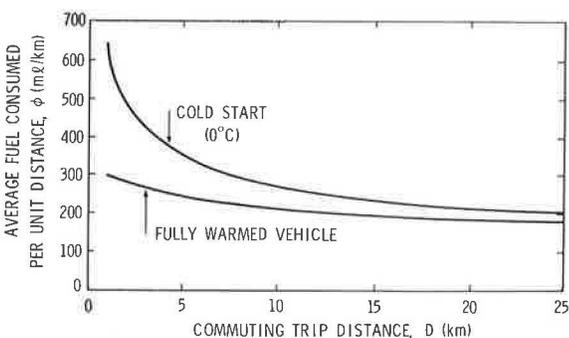


Figure 7. Estimated cumulative average fuel consumed per unit distance versus commuting trip distance for cold start and warm start.



who are more knowledgeable about fuel consumption than the general public, and their performance may not be indicative of the results that would be obtained by typical drivers. It is also important to investigate the effect on the overall traffic system of any alteration in driving patterns on the part of a large number of drivers. Drivers attempting to minimize fuel consumption might cause an increase in the fuel consumption of the total traffic system.

Fuel Consumed in Commuting Trips

Because about one-third of all distance driven is for trips to and from work (6), the question of how the fuel consumed on such commuting trips depends on the trip distance is of obvious interest. Two factors that affect the fuel consumed in commuting trips in urban traffic are discussed. First, a commuting trip normally starts with the vehicle cold. Second, the average speed of a commuting trip is an increasing function of distance (9, 10).

More fuel is consumed on cold start trips than is predicted by equation 2, which presumes a fully warmed vehicle. Let F_c be the measured total fuel consumed in a cold start trip of distance D and trip time T . The excess fuel consumed because of the cold start, ΔF , over the predicted fuel consumed with warm start can be estimated by

$$\Delta F = F_c - F \tag{5}$$

where F is given by equation 2. Equation 5 gives the excess fuel consumed because of a cold start for test runs conducted in real traffic or in commuting trips without the need to replicate the trip with a fully warmed up vehicle as is usually done in cold start fuel consumption studies (7, 8).

Forty-one cold start trips, including commuting trips, were made with ambient temperature ranging from -17 to 30°C . For each trip, the excess fuel ΔF was estimated at each kilometer increment of distance. For a given trip distance D , ΔF decreased with increasing ambient temperature θ . A linear regression of ΔF on θ at each value of D gave typical correlation coefficients of about -0.66 . The estimated excess fuel consumed because of the cold start versus the distance traveled for 0, 10, and 20°C ambient temperatures is shown in Figure 6.

The second factor that affects fuel consumed in commuting is the dependence of average commuting trip speed on distance (9, 10). Published data for trips to and from the General Motors Technical Center, Warren, Michigan (9), were used to estimate the average speed of a commuting trip of distance D . By combining this result with the information in Figure 6 we deduce the excess fuel consumed on a cold start commuting trip. The estimated total fuel consumed in the cold start commuting trip, F_c , is then given by

$$F_c = \Delta F + k_1 D + k_2 T \tag{6}$$

where $T = D/\bar{v}$. Figure 7 shows ϕ (i.e., F_c/D) plotted versus D for cold start commuting trips at 0°C ambient temperature and for warm start commuting trips. If \bar{v} were independent of trip distance, the warm start curve would be a horizontal line. Some illustrative examples derived from Figure 7 are given below:

Distance	Distance Ratio	Fuel Consumption Ratio	
		Warm	Cold
10 km versus 5 km	2	1.75	1.56
15 km versus 5 km	3	2.43	2.06

For example, a 10-km commuting trip requires only 56 percent more fuel than a 5-km commuting trip for cold starts and not 100 percent more as the simple distance ratio would suggest.

This large effect is of importance in estimating commuting fuel consumption associated with different residential and work location patterns.

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