

Fuel Saving Potential of Low-Cost Traffic Engineering Improvements

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The objective of this project was to develop priorities for certain low-cost urban traffic engineering improvements based on their potential for saving fuel. The study procedure involved the use of a test vehicle equipped with a precision fuel meter. Test runs were conducted on selected routes in Albuquerque and in off-road simulated conditions. Data from the field tests were processed with linear regression techniques to develop a model for the prediction of a rate of fuel consumption. The principal independent variable in the model is the rate of vehicular motion, although a correction for gradient is required to provide consistency between the model and the results of field tests. The model was applied to certain traffic improvements that could not be evaluated through before-and-after field tests. With respect to fuel saving, the most cost-effective improvements were found to be flashing signal operation, use of longer curb radii, and better use of existing coordinated signal systems and one-way streets. Pedestrian grade separations at school crossings cannot be justified solely on the basis of fuel savings, and the operation of neighborhood traffic diverters was found to result in an excess of fuel use.

Virtually all studies of energy consumption in the United States report that approximately 25 percent of the energy used is devoted to transportation. Although all modes contribute to this consumption, highway vehicles account for nearly 80 percent of the transportation-related energy consumption (1). These facts, coupled with the exclusive reliance of highway vehicles on petroleum products, have prompted a broad-based examination of methods for reducing automotive fuel consumption. The technical literature reports on a variety of techniques for reducing automotive fuel consumption. The principal methods are increases in efficiency of energy conversion and load factors, shifts to more efficient modes, reduction in travel, and improvement in use patterns (2). Many specific programs within these five categories have been proposed, and potential fuel savings from some programs have been estimated. The consensus appears to be that, during the next decade, improvement in the fuel economy of new vehicles will have the most pronounced effect.

The principal involvement of the traffic engineer is in the area of improved use patterns, which encompasses most improvements to traffic flow. Many traffic engineers feel that their actions can help reduce fuel consumption. The technical literature related to the anticipated benefits from traffic engineering improvements abounds with citations of the energy-saving merits of the improvements. In the typical case, however, the benefits are not quantified, nor is a basis proposed for such a quantification. The qualitative basis for potential fuel savings due to roadway improvements include the following:

1. Studies of fuel consumption, beginning in the 1930s and continuing through the 1960s, on the effects of major geometric changes, which have been updated economically but not technically (3);
2. Theoretical studies that use computer modeling techniques for vehicle flow and fuel consumption;
3. Common sense, which suggests that reduced vehicle idling time and more uniform travel speeds will reduce fuel consumption; and
4. Limited recent real-world studies of urban fuel consumption.

Although the work that has gone into the previous studies is significant, the studies have deficiencies

that limit their usefulness in 1980. The changes in vehicle mix and performance characteristics limit the value of older data. In addition, the transportation system management (TSM) improvements that are being emphasized today differ significantly from the major projects that were studied extensively earlier. And finally, some difficulties remain with the quality of data used in the computer-modeling procedures.

The purpose of this study was to develop a cost-effectiveness hierarchy of urban traffic engineering improvements on the basis of their fuel-saving potential. Although the study was conducted in Albuquerque, the findings may have broader applicability.

STUDY PROCEDURE

The examination of traffic improvements when the individual savings per vehicle are small requires the use of a field study of actual and simulated traffic conditions. For this purpose, a precision displacement fuel meter was purchased. The meter, which is factory calibrated to be accurate over all expected automotive fuel-consumption rates, measures fuel consumption in cubic centimeters and simultaneously records fuel temperature and elapsed time. The unit consists of an underhood transducer assembly and a display unit mounted on the dashboard. All fuel readings were adjusted for the equivalent fuel consumption at 15.6°C for both fuel and air temperature (4) by using procedures established by the Society of Automotive Engineers.

The meter was installed in a 1977 model compact vehicle. The fuel economy reported by the U.S. Environmental Protection Agency (EPA) for this vehicle is close to the average for 1977 compact vehicles and is slightly less than that for all 1977 vehicles. At the time this project was completed approximately 28 percent of the vehicles on the road were newer than the test vehicle. The vehicle was kept in good condition throughout the field testing period, and no major repairs were made during testing. For all field tests, cold tire pressure was kept at 2.25 kg/cm².

In the initial stages of test vehicle use, a series of constant speed runs was made on two test routes for calibration purposes. Test route 1 parallels the Rio Grande River north of Albuquerque and has a grade of 0.13 percent, and test route 2 is perpendicular to the Rio Grande River and has a significant (4.11 percent) grade. Calibration runs were conducted on test routes 1 and 2 during the early morning hours to minimize the influence of other traffic. On test route 1, a series of constant speed runs was made at 8 km/h speed increments from 32 to 96 km/h, and at 113 km/h. On test route 2, runs were made at 16 km/h increments from 32 to 96 km/h.

The field data from these and subsequent test routes were coded onto computer cards. The coding format varied slightly among the test routes, but the basic information common to all test routes included route number, date, starting time, fuel consumption, temperatures, and travel time. For certain test routes, incremental fuel consumption and travel time, delay, acceleration time, curb radius,

and number of delayed vehicles were also coded. Although the data processing differed somewhat for the various test routes, many of the processing steps were similar. A general flow chart for the processing is presented in Figure 1. Initially, fuel data were adjusted for temperature according to Society of Automotive Engineers procedures. Fuel-consumption rates, based on adjusted fuel consumption and test route length, were calculated. The commonly specified fuel-consumption value, miles per gallon, was calculated but it is not convenient for analysis purposes. Its reciprocal, gallons per mile, is more useful, but is not consistent with the values reported by other researchers who used the metric system. Several technical articles use liters/100 km or milliliters per kilometer, neither of which is consistent with established procedures for specifying metric values. The fuel-consumption rate, which is proper dimensionally, is cubic millimeters per meter. This rate, which is numerically equal to the value for milliliters per kilometer, was used in this research. For comparison purposes, a vehicle that has a fuel economy of 20 miles/gal has fuel-consumption rates of 0.05 gal/mile and 117.6 mm³/m.

The processing of data continued with the printing of the original data and calculation of fuel-consumption rates. The data were then separated by direction of travel or field test condition. Separate calculations of average statistics were performed by direction or condition. In some cases, regression analyses were performed with the fuel-consumption rate as the independent variable. In these cases, the program prepared plots of the observed and predicted rates. The t-test was performed to compare appropriate variables by direction or condition. In certain cases, the data were processed by using correlation or discriminant analyses.

Following these runs, the engine oil was changed and the vehicle was taken to an authorized Ford dealer for a minor tuneup. The spark plugs and air cleaner were replaced, and the fuel and ignition systems were adjusted to the manufacturer's specifications. The vehicle was then retested on routes 1 and 2. The fuel-consumption rates for these test routes are plotted in Figures 2-4. As shown in Figure 2, the minimum fuel-consumption rate on test route 1, which is virtually level, is in the range of 48-64 km/h. Figure 3 indicates that the minimum fuel-consumption rate occurs near 64 km/h on the 4.1 percent downgrade and near 48 km/h on the 4.1 percent upgrade. Both figures indicate that the tuneup had little effect on fuel consumption for this test vehicle. For test route 1, the average fuel-consumption rate for all speeds changed from 104.92 mm³/m (before) to 103.24 mm³/m (after), a 1.6 percent decrease. The change is not statistically significant, and as indicated by Figure 2, at some speeds the fuel-consumption rate increased in the after study. On test route 2, the fuel-consumption rates in the after study were 2 percent higher on the upgrade and 6.5 percent lower on the downgrade. On this route, the round-trip fuel-consumption rate was 0.2 percent higher in the after study. A comparison of the round-trip fuel-consumption rates on test route 1 versus the similar data for test route 2 showed that, for comparable running speeds, rates averaged 25 percent higher on the grade. In other words, the fuel saved while traveling downgrade is less than the excess fuel used on the upgrade.

All of the data for test route 1 were combined and are shown in Figure 4. The combining of data is acceptable because the route is level, and there was no significant difference between the before and after tests. The minimum fuel consumption occurs at approximately 48 km/h, although the fuel-consumption curve is nearly constant at 93 mm³/m between 48

and 56 km/h. This is the speed range that should be maintained to minimize fuel consumption. Figure 4 clearly shows the fuel penalty associated with higher speeds. What is less obvious from the graph is the penalty associated with low speeds. It has been reported that elimination of speeds less than 32 km/h would reduce vehicle fuel consumption by more than that due to the the 88-km/h speed limit (5). This has led to the suggestion that the adoption and enforcement of a minimum speed limit should be considered as part of a fuel-saving program. The apparent problem with the 88-km/h speed limit is achieving motorist compliance; however, the most serious problem with a minimum speed limit of 24 or 32 km/h is for the traffic engineer to provide a roadway environment that would permit motorists to comply with the limit. As a practical matter, a minimum speed limit for urban streets is not obtainable. However, the objective of reducing driving at low speeds, complete stops, vehicle idling time, and keeping speeds near the optimum level of about 48 km/h can be partly accomplished through the application of traffic engineering principles.

Since money for traffic engineering improvements in an urban area such as Albuquerque is limited, it is important to know which types of improvements have the most substantial effect on fuel consumption. This information can assist in establishing priorities for improvements. To evaluate the effect of various types of traffic-engineering improve-

Figure 1. General flow diagram for data analysis.

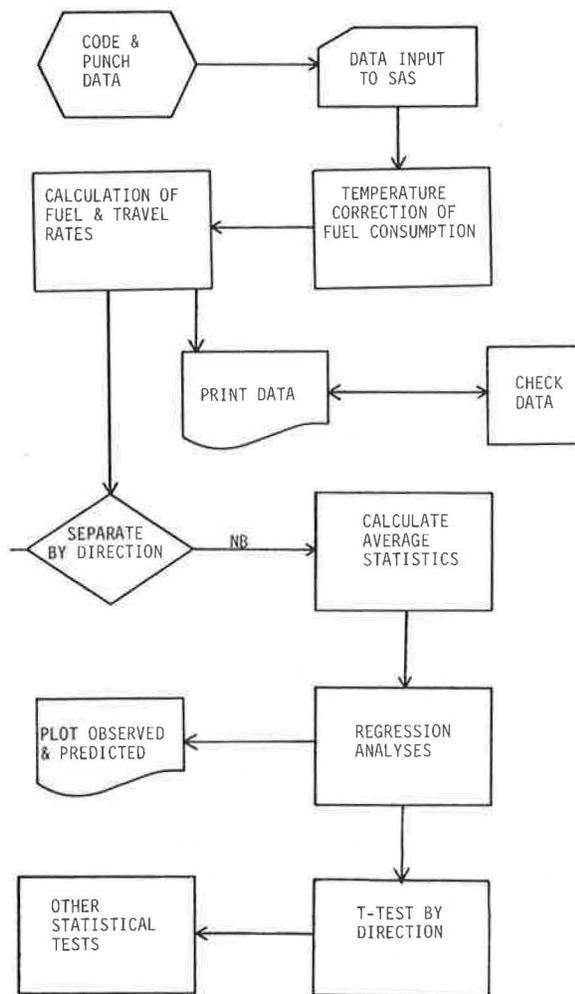


Figure 2. Fuel-consumption rates at selected constant speeds on test route 1, before and after vehicle tuneup.

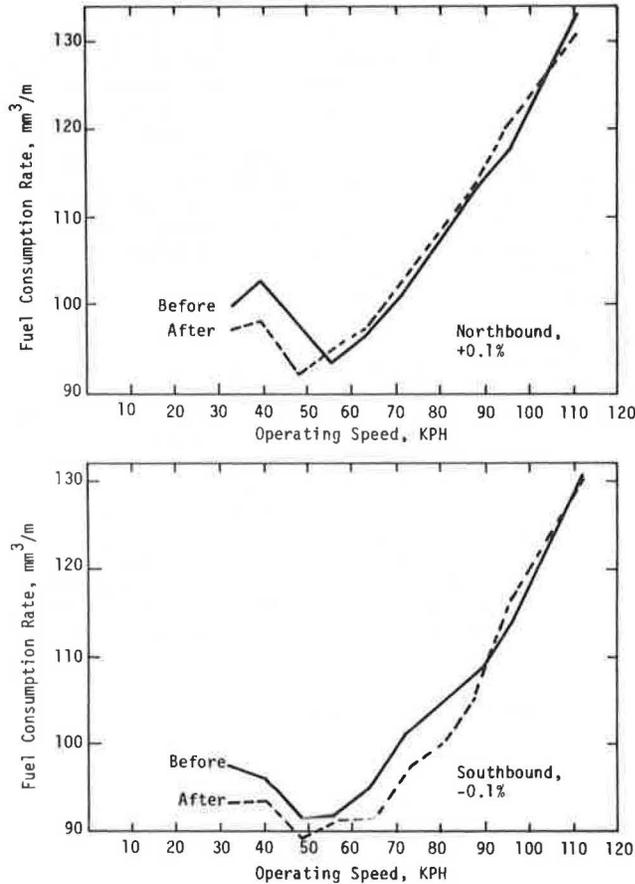


Figure 3. Fuel-consumption rates at selected constant speeds on test route 2, before and after vehicle tuneup.

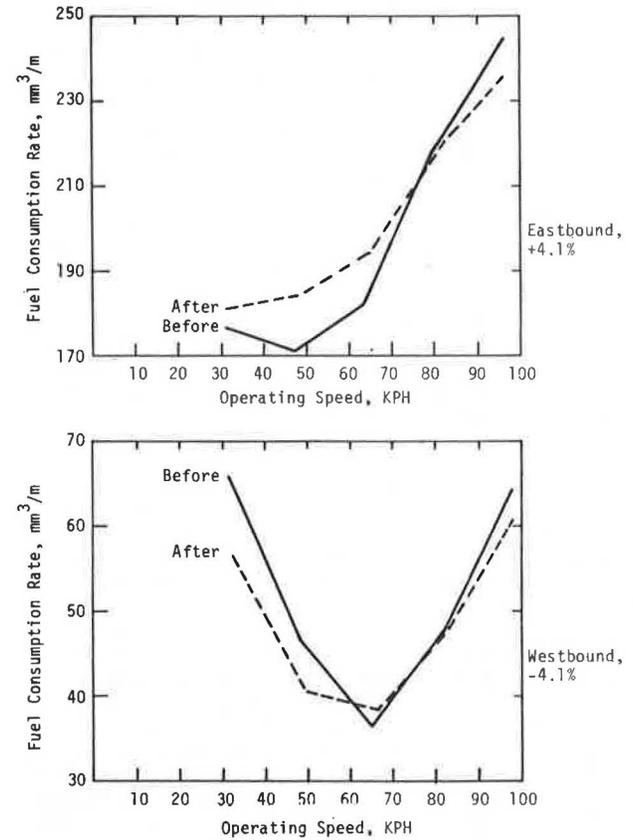
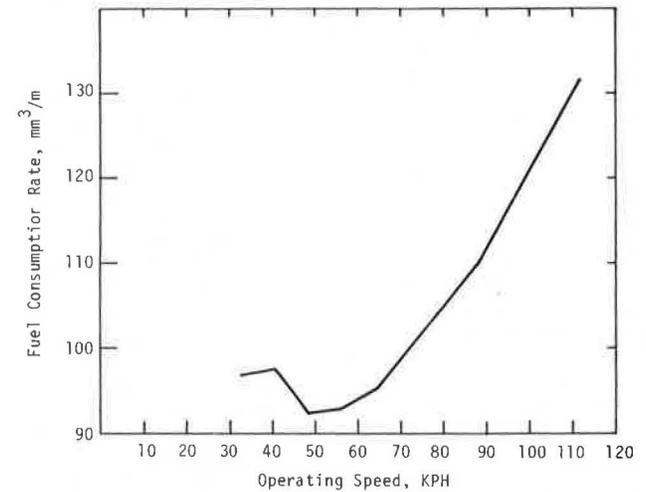


Figure 4. Fuel-consumption rates at selected constant speeds on level test route—combined results from all test runs.



ments, a number of field experiments were conducted by using the instrumented test vehicle.

Effect of Stop Sign

One of the most visible forms of traffic control is the stop sign. Its use is required by law in certain cases, and the Manual on Uniform Traffic Control Devices provides some guidelines for the use of stop signs. Numerous studies have shown that stop signs will have only a limited effect on the occurrence of traffic accidents. It has also been established that the installation of stop signs for the purpose of controlling vehicular speeds does not achieve the desired intent. Despite these facts, citizens frequently request the installation of stop signs to solve perceived traffic problems.

A disadvantage of the installation of stop signs is that extra fuel is consumed by a vehicle to decelerate to a stop and then regain speed. Winfrey (6) reports data from the mid-1960s that is based on a 1815-kg passenger car that has an optimum fuel consumption of 100.7 mm³/m. He reports the excess fuel consumed by this vehicle in one speed change cycle, which is defined as the process of reducing speed from and returning to an initial speed. In the case of a speed cycle from an initial speed of 56 km/h to a stop and back to 56 km/h, the vehicle consumed 37.2 cm³ more fuel than by driving at a constant speed of 56 km/h. Travel time was increased by 14 s for this speed change, assuming no delay caused by other vehicles.

Two parallel test routes were established to

determine the current effect of stop signs on fuel consumption. Both routes were approximately 1.26 km long and had +2 percent grades in the eastbound direction. Test route 3 had no stop signs, and test route 4 had a stop sign at one intersection. A comparison of the fuel-consumption and travel time data for the two test routes under conditions of low traffic volume is presented in Table 1.

The excess fuel consumed by the 56-km/h speed

change cycle was 36.1 cm³ eastbound and 37.8 cm³ westbound. The average of 37 cm³ and the excess travel time (13.5 s) are both in close agreement with the values reported by Winfrey. The data suggest that, although fuel consumption is clearly related to the grade, the excess fuel consumption associated with the speed change cycle is independent of the grade.

Effect of 24-km/h School Zones

Albuquerque has approximately 120 posted school zones where the speed limit is reduced to 24 km/h during the hours when children are crossing. Although crossing hours vary among schools, the lower speed limits are typically in effect from 8:00 to 9:00 a.m., during the lunch period, and from 3 to 4 p.m., for a total of 3 h. The zones, which are controlled by adult crossing guards, are typically on arterials that normally have posted speed limits of 48-56 km/h. The zones vary in length, but a survey found that they averaged 130 m. A 1978 study found that motorists generally comply with the speed limit (average speed = 26.5 km/h), but that they quickly regain normal speeds once they have left the zone. It is hypothesized that compliance with the reduced speed limit is enhanced by the presence of the adult guard and by the short zone length, which is marked by appropriate traffic signs.

There is no doubt that the lower speed limit causes excess fuel use. Winfrey (6) reports that a speed change cycle from 56 to 24 km/h and returning to 56 km/h uses 24.7 cm³ excess fuel. This estimate does not include the excess fuel used while traveling through the school zone, or the effect of a complete stop if children are crossing. Since the lower speed through the school zone defeats one of the objectives of a coordinated signal system, as motorists move through a progressive system, they may encounter delay and excess fuel consumption at nearby signalized intersections.

To evaluate this situation, test route 5 was established along a 1.63-km roadway section that has a 124-m school zone near the middle of the section. The route has a 1.4 percent grade eastbound, and a normal speed limit of 56 km/h. The test route was subdivided into 3 sections, one on the approach to each of the signalized intersections at the terminal points and a central section that included the school zone. Separate fuel and travel time data were collected by direction for each section. The data for the center (school zone) section of test route 5 are shown in Table 2.

The excess fuel used due to the operation of the school zone was found to be 17.1 cm³ eastbound and 28.7 cm³ westbound. Travel time through the section varied as a function of whether a complete stop was required to permit children to cross. The travel time averaged 23 s longer when the school zone was in operation. The excess fuel consumption through the school zone is less than that that would be predicted from Winfrey's data. Further, analysis showed that the effect of the school zone on progressive movement of traffic on this test route was negligible. In other words, the entire difference in both fuel consumption and travel time for the total test route was attributable to the section that contained the school zone.

One-Way Streets

The technical literature (7) suggests that one-way streets offer the potential for reduced fuel consumption, improved operations, and increased capacity. Because of the many variables involved in the design and operation of one-way streets, the tech-

Table 1. Average data for test routes 3 and 4.

Item	Direction	No Stop Sign	With Stop Sign
Fuel consumption (cm ³)	Eastbound	162.9	199.0
	Westbound	59.9	97.7
Rate (mm ³ /m)	Eastbound	131.3	156.9
	Westbound	48.3	77.1
Travel time (s)	Eastbound	79.6	93.4
	Westbound	79.3	92.4

Note: Grade of roadway is +2 percent eastbound and -2 percent westbound.

Table 2. Average data for center section of test route 5.

Item	Direction	Without School Zone	With School Zone
Fuel consumption (cm ³)	Eastbound	152.5	169.6
	Westbound	85.3	114.0
Rate (mm ³ /m)	Eastbound	126.3	140.5
	Westbound	70.7	94.4
Travel time (s)	Eastbound	76.9	102.6
	Westbound	75.6	96.3

Note: Grade of roadway is +1.4 percent eastbound and -1.4 percent westbound.

nical literature does not indicate the amount of fuel savings that can be obtained from operation of a one-way street. The ideal approach to evaluating fuel savings would be through before-and-after studies. However, since Albuquerque was not planning to implement any new one-way-street systems during this project, it was necessary to select existing one-way streets and generally comparable two-way streets. It is not possible to choose routes that are completely identical, but two pairs of routes were selected as the best available alternatives. Test routes 6 (one way) and 7 (two way), eastbound and westbound in a suburban-commercial area, had some differences in traffic volume and roadside development. Test routes 9 (one-way) and 10 (two way), northbound and southbound in a central business district (CBD) fringe area, had similar geometric and operational characteristics.

A series of test runs was conducted to compare the fuel-consumption effect of the one-way streets. The results are presented in Table 3. The excess fuel consumption on test route 7 versus the one-way couplet is 36.2 cm³ eastbound and 58.9 cm³ westbound. While these differences are statistically significant, the actual differences are probably even more substantial because test route 6 had some rise-and-fall, but the two-way route had an essentially constant grade. The fuel saving is primarily attributable to the smoother flow of traffic on the one-way couplet, which resulted in less delay. At a constant speed of 56 km/h, route 6 could theoretically be driven in 194 s. The actual average travel time was 210 s, only 8 percent above the theoretical minimum. On the other hand, the travel time on route 7 was 35 percent higher (75 s) than on the one-way couplet. The additional travel time, much of which was spent idling at traffic signals, accounts for a substantial part of the increased fuel use on the two-way street. Based on the observed idle fuel-consumption rate of 0.53 cm³/s, an additional 75 s of idling time would use approximately 40 cm³ of fuel. The remainder of the observed difference in fuel consumption is due to the excess used during acceleration.

As shown in Table 3, there is very little difference between the average fuel and travel time

Table 3. Average data for one- and two-way streets—test routes 6, 7, 9, and 10.

Item	Direction	One-Way Street	Two-Way Street
Fuel consumption (cm ³)	Eastbound	350.4	386.6
	Westbound	240.3	299.2
	Northbound	201.5	207.8
	Southbound	178.3	195.3
Rate (mm ³ /m)	Eastbound	115.2	132.7
	Westbound	79.4	102.9
	Northbound	119.3	125.2
	Southbound	106.5	117.7
Travel time (s)	Eastbound	207.5	279.8
	Westbound	213.8	291.5
	Northbound	166.4	181.1
	Southbound	168.0	210.2

characteristics on test routes 9 and 10 (northbound and southbound directions). Although the fuel consumption is slightly less on the one-way couplet and could be explained by the slightly longer travel times on test route 10, further testing showed that, with the exception of the southbound travel time, none of the apparent differences are statistically significant.

The explanation for the lack of a fuel savings on these one-way streets in the CBD fringe is fairly straightforward. The traffic signals along the one-way couplet are not operated in a coordinated manner. Because of the lack of signal coordination that is generally obtainable on a one-way street, the potential fuel saving of this traffic control technique is not being achieved on this couplet.

Although this one-way couplet is not producing any benefits, it is still operating at a significantly better rate of fuel consumption than more congested two-way streets in the CBD. This is verified by the results from test route 13, a 1.08-km section of the main street through downtown. The route, which carries two-way traffic and has a -0.14 percent grade in the westbound direction, has six traffic signals. The average fuel-consumption rate on this section was 170 mm³/m. This is the highest rate found for any extended test route evaluated in this study. The rate is 50 percent higher than for the one-way couplet (test route 9) and is 30 percent higher than the average rate of fuel consumption for this test vehicle operating at a constant speed of 113 km/h. This is a further indication that low travel speeds, such as average 24 km/h on test route 13, have an extremely adverse effect on fuel consumption.

Curb Radii

One of the factors that influences intersection operation is turning vehicles. The standard conditions for capacity calculations at signalized intersections assume that an average of 10 percent of the approaching traffic turns right and another 10 percent turns left. Actual turning percentages are dependent on time of day and the particular intersection, but percentages higher than those cited above are found at many locations.

A vehicle approaching an arterial intersection must slow considerably to make a turn. In the case of a vehicle turning right that approaches the intersection in the right-most lane available for moving traffic and turns into the nearest lane on the cross street, the extent to which the vehicle must slow is primarily determined by the radius of the curb. At most right-angle intersections, the curbline is described by a constant radius circular arc. Measurements in older parts of Albuquerque

found that most curb radii were between 3.5 and 5 m.

Winfrey (6) presents some data on the excess fuel consumption due to 90° corners. The data are of little value for most urban intersections because they are for radii from 7.6 to 76 m, in 7.6-m increments. Because of physical limitations, pedestrian considerations, and other factors, radii in excess of 12 m are impractical for unchannelized urban intersections.

The basic advantage of a larger curb radius is that a vehicle turning right does not have to slow down as much to safely negotiate the turn. On dry pavement, a vehicle can safely make a 90° turn with a 15-m radius at approximately 27 km/h, while the same turn with a 1.5-m radius requires a speed of 10 km/h or less. The travel at low speed plus the acceleration back to normal speed will result in excess fuel use. To evaluate this situation, an off-road test was conducted in a large, vacant parking lot. This route, identified as test route 8, consisted of two sections 53 m in length at right angles to each other. Various curb radii, from 1.5 to 15 m in 1.5-m increments were laid out and delineated with chalk marks and traffic cones. A series of 12 test runs were conducted for each radius. During the test run, the vehicle entered the test route at 32 km/h, slowed to an appropriate speed to safely negotiate the curve, and accelerated back to 32 km/h.

The results of this test are summarized in Table 4. The fuel-consumption rate shows a dramatic decrease, from 201 mm³/m at 1.5 m to 103 mm³/m at 15 m. The fuel-consumption rate for the 15-m radius, which was achieved with an average travel speed of slightly less than 32 km/h, is consistent with the values found on test route 1 for constant speed operation at 32 km/h. Although the use of 15-m curb radii is not generally practical in an urban area, the data in Table 4 show a significant reduction in fuel-consumption rate for intermediate values of the radius. The reduction in travel time is minimal. As shown in Table 4, the change is only 5 s with an increase in the radius from 1.5 to 15 m.

Turning Movements

In addition to the curb radii, another factor that can affect the fuel consumption of turning vehicles is the provision of exclusive turn lanes. These exclusive lanes are most commonly used near the center of the roadway for vehicles turning left, but at some locations they are installed near the edge of the roadway for vehicles turning right. They are frequently employed at signalized intersections, but on several major arterials in Albuquerque they are installed at nonsignalized intersections and at entrances to major traffic generators.

The most suitable method for evaluating the effects on fuel consumption of exclusive turn lanes would be by a before-and-after study at an improved intersection. Since this was not possible in Albuquerque during the study period, the effect of an exclusive right-turn lane was evaluated on test route 11, a pair of opposing approaches to a major intersection. Traffic volumes are similar on both approaches, but only the south approach had an exclusive right-turn lane. The test routes consisted of a 0.16-km section that included the approach to the intersection and a short distance around the corner. Test runs were conducted alternately, by direction, during both the morning and the evening peak periods. The average data for this test route are presented in Table 5.

There is a fuel saving for the exclusive right-turn lane during the morning peak period; however, during the evening peak period, fuel consumption is

Table 4. Fuel-consumption effect of various curb radii.

Radius (m)	Fuel (cm ³)	Rate ^a (mm ³ /m)	Travel Time (s)
1.5	21.9	201.1	18.0
3	20.4	188.0	16.9
4.5	19.4	180.5	16.4
6	17.9	167.9	15.6
7.5	15.0	140.9	14.7
9	14.7	139.3	14.1
10.5	13.8	131.5	13.7
12	12.3	118.1	13.2
13.5	11.1	107.0	13.0
15	10.6	103.2	13.0

^a Rate includes correction for test route length, which varies because of radii and assumed vehicle placement at the center of a 3.6-m lane, from 109 m at a 1.5-m radius to 103 m at a 15-m radius.

Table 5. Fuel-consumption effect of exclusive right-turn lane.

Item	Time	Approach	
		South	North
Fuel consumption (cm ³)	Morning	14.9	25.0
	Evening	24.1	22.2
	Both	18.6	23.9
Rate (mm ³ /m)	Morning	93.0	156.0
	Evening	150.9	138.6
	Both	116.2	149.1
Travel time (s)	Morning	20.9	35.8
	Evening	31.4	33.4
	Both	25.1	34.9

slightly higher. Statistical testing showed that the morning differences were significant, but those in the evening were not. The reason for the lack of fuel saving in the evening peak is attributable to the substantially higher volumes on the south approach at this time of day. On the average, there were two vehicles in the queue in the exclusive right-turn lane versus only one vehicle in the right lane queue on the north approach. Because of high eastbound evening volumes on the intersecting street, opportunity for turning right on red from the south approach was limited. Depending on traffic conditions, individual test runs recorded widely varying amounts of fuel consumption. On the south approach, fuel consumption ranged from a minimum of 5 cm³ to a maximum of 42 cm³; on the north approach, values ranged from 9 to 60 cm³.

FUEL CONSUMPTION MODEL

Since every possible traffic improvement cannot be tested, it is appropriate to develop a model of fuel consumption that can be used to estimate the effect of various improvements. The technical literature suggests that the rate of fuel consumption is related to the reciprocal of speed. One source reports that this type of relation applies to urban conditions and speeds up to approximately 56 km/h. This speed corresponds to a rate of motion of 64 ms/m (8).

To test this theory, the data from several hundred test runs on routes that have lengths of at least 0.8 km were analyzed by using linear-regression techniques. The resultant equation obtained for the rate of fuel consumption (R) as a function of the rate of motion (V*) was

$$R(\text{mm}^3/\text{m}) = 48.82 + 0.74 V^*(\text{ms}/\text{m}) \tag{1}$$

Although the correlation coefficient is a comparatively low 0.69, it is highly significant due to

the large sample size. However, review of a plot of observed versus predicted rates of fuel consumption revealed that data for test routes with grades deviated substantially from predicted values. Specifically, observed fuel-consumption rates for upgrades were higher than predicted, and those for downgrades were lower than predicted.

In an attempt to correct this condition, an analysis was made of the data presented by Winfrey for fuel consumption on grades. The test vehicle used in this study has a rate of fuel consumption of approximately 92 percent of that for Winfrey's vehicle. A regression model that used Winfrey's data for grades between -4 and +4 percent and speeds between 8 and 64 km/h was developed. The model, which has a correlation coefficient of 0.97, is given by

$$R = 278.71 - 8.19S + 18.45G + 0.088S^2 + 0.66G^2 \tag{2}$$

where

- R = fuel-consumption rate (mm³/m),
- S = vehicle speed (km/h), and
- G = grade (%).

This equation was used to develop a correction factor (K) that could be applied to observed fuel-consumption rates on grades. For a specific test route with a grade (G') and a particular test run with a speed of S', the correction factor is

$$K = R(S = S', G = 0) / R(S = S', G = G') \tag{3}$$

The fuel-consumption data used to develop Equation 1 were adjusted with the appropriate correction factor, and the resultant data were processed with linear-regression techniques. The equation produced by this process has a correlation coefficient of 0.91 and is given by

$$R(\text{mm}^3/\text{m}) = 44.11 + 0.77 V^*(\text{ms}/\text{m}) \tag{4}$$

Chang and others suggested (9) that the first two coefficients in the equation have physical interpretations. The first coefficient (44.11) is the fuel consumed per unit distance to overcome rolling resistance. This coefficient, which in theory is directly proportional to the mass of the vehicle, is consistent with data reported in the technical literature. The second coefficient (0.77) is the fuel consumed per unit of time (mm³/ms) to overcome mechanical losses. This coefficient for various vehicles is reportedly a linear function of their idle fuel-consumption rate. In the case of this test vehicle, the value of this coefficient is 1.44 times the idle fuel-consumption rate.

The estimate of the fuel-consumption rate given by Equation 4 is applicable for rates of motion in excess of 64 ms/m. In comparison with the constant speed runs on test route 1, the model provides estimates that exceed the observed fuel-consumption rates for speeds of 48 km/h and less. At a speed of 56 km/h, the estimate from the equation and the observed rate are identical. The equation is not intended to be used for extended operation at constant speed, however, but is applicable to real traffic situations under stop-and-go conditions.

Strictly speaking, the estimates of fuel consumption from this model apply only to the vehicle that was used in the field tests. As previously noted, however, the size and reported fuel economy of this vehicle are near the average for all current passenger vehicles.

As would be expected, there is some variation between the results of individual test runs and the rates predicted by Equation 4. However, the equa-

tion is reliable when applied to the average values of V^* for test runs on a particular route, when adjustment is made by using Equation 3. The model predicted fuel-consumption rates quite closely (typically within 2 percent) for individual test routes. This finding is not surprising, and in fact is a bit weak, because this testing made use of subsets of the data used to develop the model. It was not possible in this project to conduct independent verification of the model.

Application of the Model

Certain traffic improvements that were initially considered for study were not directly evaluated through field studies. Some of these improvements, such as rest in red and flashing signal system operation, are not currently used in Albuquerque. Another improvement, the two-way left-turn lane, is used extensively in Albuquerque, but since such a lane was not constructed during the study period, a before-and-after study was not possible. And finally, some improvements, such as changes in speed limit, can be evaluated with the model rather than through field testing. The results of the application of the model to these and other changes, including progressive signal systems and neighborhood traffic diverters, are discussed in the project report (10).

Establishing Improvement Priorities

Under certain assumptions, the results of the field tests and application of the model permit a comparison to be made among the various improvements. In accord with the objectives of this research, the principal components used in these comparisons will be the potential for fuel saving and the relative cost of the improvement. Note that a change in traffic control that produces a fuel saving could, at certain locations, create other problems that outweigh its energy benefit. The following comparisons are therefore not intended to eliminate the need for proper engineering study, which must precede the implementation of traffic improvements. Rather, the results of the comparisons will add a new dimension to the traditional analysis of proposed improvements.

The principal basis for comparing improvements is the number of liters of fuel saved per year if one vehicle/day is affected by the change ($1/v$). Certain improvements in Albuquerque, such as a speed limit change, could easily affect several thousand vehicles per day; however, other changes, such as a neighborhood diverter, would probably affect considerably fewer vehicles per day. In computing annual benefits, it is assumed that the school zone is in operation for 180 days/year, and all other improvements are applicable for 365 days/year.

Table 6 presents estimates of $1/v$ for 10 traffic engineering improvements. A properly operated one-way-street system and signing to achieve efficient motorist use of a coordinated signal system result in the largest annual fuel saving per vehicle. Removal of an unwarranted stop sign or its equivalent, the decision not to place an unneeded stop sign, also shows a high benefit. The value of $1/v$ is considerably less for the other improvements.

The actual saving for a particular improvement is clearly a function of affected volume, the characteristics of the particular location, and driver behavior. Assumptions for typical locations led to the calculation of a realistic saving, which is presented in the third column of Table 6. The specific assumptions used in these calculations are identified in footnotes to the table. The table shows

that encouragement of proper travel speed through a progressive signal system has a high potential for fuel saving. One method for realizing this benefit would be through the posting of standard signs to advise drivers of the speed for which the signals are set. The benefit would result only if drivers observed the signs and accepted their suggestion. The benefit for through traffic from the removal of a stop sign is also substantial. The apparent benefit becomes a deficit when a stop sign that cannot be justified on technical grounds is installed in response to other pressures. The realistic saving specified for the one-way street assumes that attempts are made to divert some traffic from an existing two-way street to an existing one-way street. The benefit should be considerably larger for a new one-way-street installation. The saving associated with the pedestrian grade separation assumes moderate arterial traffic volumes during the school crossing hours. The right-turn-lane saving is for a major signalized intersection. The operation of traffic signals in a flashing mode during periods of low traffic volume results in a saving equivalent to that for an exclusive right-turn lane. The remaining improvements have comparatively small realistic savings, and the neighborhood diverter shows a negative fuel benefit. However, the importance of anticipated traffic volumes should not be overlooked in evaluating any of these improvements at a specific location. Certain situations may deviate from the assumed volumes used in the calculation of realistic savings for the general case, and in these instances it would obviously be appropriate to calculate the saving by multiplying the volume by $1/v$.

Three other criteria can be considered in the evaluation of traffic improvements. Cost per improvement is obviously important but is difficult to determine with any degree of accuracy without a thorough study at specific locations. Right-of-way, construction, and operation costs should all be considered. The extent to which a particular improvement can be used is also important. For example, pedestrian grade separations have limited applicability, but curb radii improvements could be made at a substantial number of locations. A third criterion is the other (nonfuel) benefits associated with the improvements. The traffic engineering literature suggests that many of the improvements evaluated in this project have benefits for travel time, capacity, safety, or pollution reduction. These criteria were subjectively evaluated with respect to the street system in Albuquerque, and the results are presented in Table 7.

Table 6. Annual fuel savings.

Improvement	$1/v^a$	Realistic Saving ^b
One-way street ^c	17.4	15.1
Coordinated signals ^d	17.4	30.3
Stop sign removal	13.6	26.5
School pedestrian crossing ^e	4.1	10.2
Right-turn lane	3.6	3.8
Two-way-left-turn lane ^f	3.4	1.9
Curb radius, 3-9 m	2.2	1.1
Flashing signal operation ^g	2.1	3.8
Speed limit, 40-48 km/h ^h	1.1	0 to -3.8
Neighborhood diverter	-6.8	-1.1

^aLiters of fuel saved/year/affected vehicle per day.

^bAnnual liters of fuel saved per improvement under conditions of moderate volume, reasonable motorist compliance with regulations, and other conditions listed in this paper.

^cAssume 3.2 km long, good signal coordination.

^dFor 0.8 km section, one-direction, with signing.

^eGrade separation, crossings 3 h/day.

^fOne block long, replaces previous median barrier.

^gOperation for 8 h/day versus isolated pretimed signal.

^hOptimistic assumption of motorist compliance with 40-km/h limit for $1/v$ calculation.

Table 7. Cost, applicability, and other benefits of improvements.

Improvement	Cost	Applicability	Other ^a
One-way street ^b			
New installation	High	Very limited	Very positive
Existing installation	Low	Limited	Positive
Coordinated signals ^c	Low	Limited	Neutral
Stop sign removal	Low	Moderate	Positive
School pedestrian crossing ^d	Very high	Limited	Very positive
Right-turn lane	Medium	Moderate	Positive
Two-way-left-turn lane ^e	Medium	Moderate	Very positive
Curb radius			
New installation	Low	Limited	Neutral
Reconstruction	Medium	Extensive	Positive
Flashing signal operation ^f	Low	Moderate	Uncertain
Speed limit ^g	Low	Moderate	Positive
Neighborhood diverter	Medium	Limited	Positive

^aOther benefits include travel time savings, increased capacity, improved operation, and safety.

^bAssume 3.2 km long, good signal coordination.

^cFor 0.8-km section, one-direction, with signing.

^dGrade separation, crossings 3 h/day.

^eOne block long, replaces previous median barriers.

^fOperation for 8 h/day versus isolated pretimed signal.

^gOptimistic assumption of motorist compliance with 40-km/h limit.

The results presented in Tables 6 and 7 were used to develop a general hierarchy of low-cost traffic engineering improvements to promote fuel savings. The priorities, listed below and limited to the improvements studied in this project, must be considered general in nature. The ranking differs from one that would be established on the basis of other criteria, such as safety. As noted before, the application of a particular improvement at a specific location requires a study of sufficient detail at that location.

<u>Priority</u>	<u>Improvement</u>
High	Flashing signal operation
	Larger curb radii for new installation
	Progressive signal system signing
	Diversion to existing one-way streets
	Stop sign evaluations
	Lengthening existing curb radii
	Exclusive right-turn lanes
	Installation of two-way left-turn lane
	Installation of new one-way streets
	Change urban speed limits to optimal values
	Grade separations at school crossings
Low	Neighborhood traffic diverters.

Despite these limitations, the findings summarized above warrant some consideration in the development of a traffic engineering improvement program for energy conservation.

SUMMARY

This study has found that there are modest but discernible fuel benefits associated with traffic engineering improvements. The savings are small in comparison with other programs to cut fuel consumption such as improved vehicles, vanpools, and reduced travel. However, the traffic improvements are often low in cost and have the potential for providing benefits on a daily basis for an extended time period.

The study has a deficiency that is worth noting. The time and financial constraints on the project, coupled with the nature of traffic improvements made in Albuquerque during the study period, limited the types of improvements that were evaluated. There are clearly other TSM improvements that should be evaluated in a more comprehensive evaluation of this subject.

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Assessment of Neighborhood Parking Permit Programs as Traffic Restraint Measures

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Residential parking permit programs have become an important component of traffic restraint schemes designed to improve the social and environmental

characteristics of neighborhood areas. By restricting nonresident and commercial vehicle parking, such programs are effective in controlling the use of the