SUMMARY AND RECOMMENDATIONS

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

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

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

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

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Effect of Freeway Work Zones on Fuel Consumption

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

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

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

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

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

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

UNDERSATURATED CONDITIONS

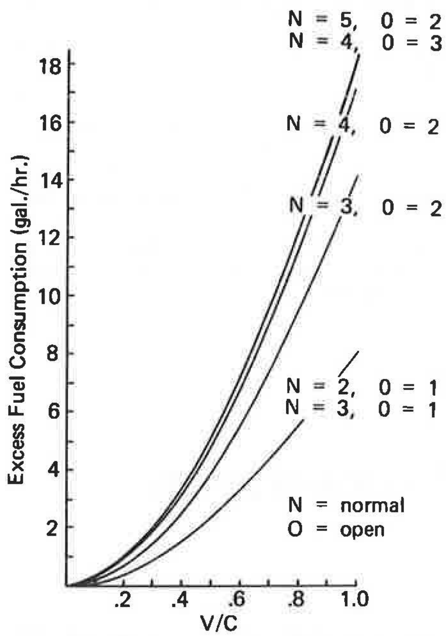
During time periods when the volume-capacity ratio

Table 1. Excess gallons of gasoline consumed per slowdown speed-change cycle—passenger car.

Speed (mph)	Excess Gasoline Consumed (gal) by Amount of Speed Reduction Before Accelerating Back to Speed (mph)					
	10	20	30	40	50	60
20	0.0032	-	-	-	-	-
30	0.0035	0.0062	-	-	-	-
40	0.0038	0.0068	0.0093	-	-	-
50	0.0042	0.0074	0.0106	0.0140	-	-
60	0.0046	0.0082	0.0120	0.0155	0.0190	-
70	0.0051	0.0090	0.0130	0.0167	0.0203	0.0243

Note: Data derived from Claffey (4) for the composite passenger car representative of the following vehicle distribution: 20 percent large cars, 65 percent standard cars, 10 percent compact cars, and 5 percent small cars.

Figure 1. Excess fuel consumption due to speed-change cycles—undersaturated conditions.



(V/C) of the work zone is less than one, there are two major factors that have an effect on the amount of fuel consumed. These two factors are (a) an increased fuel consumption due to speed-change cycles and (b) a decreased fuel consumption as a result of vehicles traversing the work zone at a reduced speed. The algebraic sum of the effects of these two factors is the total excess fuel consumed during undersaturated conditions. In many cases, particularly for longer work zones, this sum will be negative, which indicates a net fuel savings that results from freeway work zones during undersaturated traffic flow conditions.

Effect of Speed-Change Cycles

Due to the reduced capacity of a multilane facility when one or more lanes are closed for construction or maintenance, the operating speed of vehicles in the affected section is decreased. The combined effect of decelerating to and accelerating from this reduced speed is a net increase in fuel consumed when compared with the consumption at a constant speed through the normal section.

If the V/C of a work zone is known, an estimate of the operating speeds can be obtained from idealized speed-volume relations. Studies have shown that the speed-volume relation for uninterrupted flow conditions on multilane highways can be reasonably represented by a straight line (2). This line extends from the average highway speed at V/C equal to zero down to 30 mph at V/C equal to one. From this linear relation, the operating speed on any multilane highway is computed as follows:

$$OS = AHS - (V/C)(AHS - 30) \tag{1}$$

where OS is the operating speed (mph) and AHS is the average highway speed (mph).

At a given volume, the difference between the operating speed obtained with the normal capacity of the roadway and that obtained with the reduced capacity due to a lane closure is the amount of speed reduction caused by the lane closure. Capacities through freeway work zones for the six lane-closure situations considered in this study were measured by Dudek and Richards (3). These capacities are given in the table below (3):

No. of Lanes		Avg Capacity	
Normal	Open	Vehicles per Hour	Vehicles per Hour per Lane
2	1	1340	1340
3	2	3000	1500
3	1	1130	1130
4	3	4560	1520
4	2	2960	1480
5	2	2740	1370

These capacities were used in this study to compute speed reductions caused by the lane closures as follows.

For example, suppose the normal capacity of a two-lane section of freeway is 4000 vehicles/h and the average speed on the facility is 55 mph. If one lane is closed, the capacity in the work zone is reduced to 1340 vehicles/h (from the table above). If the hourly volume on the section is 800 vehicles/h, the V/C for the normal and reduced capacity conditions would be computed as follows:

$$V/C_{normal} = 800/4000 = 0.20 \tag{2}$$

$$V/C_{reduced} = 8/1340 = 0.60 \tag{3}$$

From Equation 1, the operating speeds for these two conditions would be 50 mph in the normal section and 40 mph in the reduced section. Thus, the amount of the speed reduction caused by closing one lane of the two-lane section of freeway would be 10 mph.

The excess fuel consumed as a result of a slowdown cycle is a function of not only the amount of speed reduction but also the operating speed before and after the reduction. In the example above, this speed would be 50 mph. Table 1, which was derived from data presented by Claffey (4), shows the gallons of excess fuel consumed per speed-change cycle by passenger cars. From this table, the amount of excess fuel consumed per passenger car can be determined for any combination of speed reduction and normal operating speed. Then, multiplying the value obtained from Table 1 by the hourly volume gives the excess fuel consumed per hour by passenger car speed-change cycles.

Based on a normal freeway capacity of 2000 vehicles/h/lane and the work-zone capacities shown in the in-text table above, Figure 1 shows the relation between excess fuel consumption per hour due to speed-change cycles and the work-zone V/C for the six lane-closure situations. By using this figure, the excess fuel used per hour can be determined directly. For the example given above, the excess

Figure 2. Fuel savings due to speed reduction—undersaturated conditions.

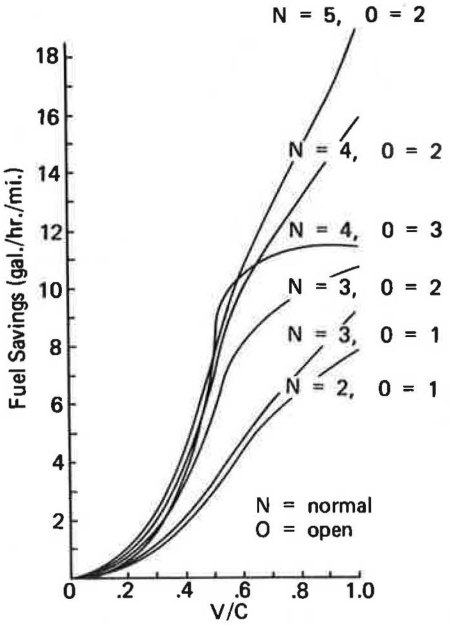


Table 2. Truck factors for fuel consumption due to speed-change cycles—undersaturated conditions.

V/C	Truck Factors at Following Percentages				
	0	10	20	30	40
0.1	1.00	1.75	2.50	2.90	3.28
0.2	1.00	1.74	2.48	2.85	3.22
0.3	1.00	1.71	2.42	2.80	3.16
0.4	1.00	1.70	2.40	2.75	3.10
0.5	1.00	1.68	2.36	2.70	3.04
0.6	1.00	1.66	2.32	2.65	2.98
0.7	1.00	1.65	2.30	2.65	2.98
0.8	1.00	1.63	2.26	2.60	2.92
0.9	1.00	1.61	2.22	2.55	2.86
1.0	1.00	1.58	2.16	2.45	2.74

fuel consumed per hour when a two-lane freeway is reduced to one lane with a V/C of 0.6 is 3.4 gal/h.

Effect of Reduced Operating Speeds

At speeds greater than 30 mph, the rate of fuel consumed by passenger cars increases with operating speed, as shown in the table below, which was derived from data presented by Claffey (4) (note, data are for a composite passenger car representative of the following vehicle distribution: 20 percent large cars, 65 percent standard cars, 10 percent compact cars, and 5 percent small cars):

Uniform Speed (mph)	Fuel Consumption (gal/mile)
10	0.072
20	0.050
30	0.044
40	0.046
50	0.052
60	0.058
70	0.067

Thus, the reduced operating speeds associated with e lower capacities of freeway work zones will se a fuel savings. The difference between the

Table 3. Truck factors for fuel consumption as affected by speed—undersaturated conditions.

V/C	Truck Factors at Following Percentages				
	0	10	20	30	40
0.1	1.00	1.52	2.03	2.56	3.08
0.2	1.00	1.51	2.02	2.53	3.04
0.3	1.00	1.48	1.96	2.44	2.92
0.4	1.00	1.31	1.62	1.93	2.24
0.5	1.00	1.34	1.68	2.02	2.36
0.6	1.00	1.28	1.56	1.84	2.12
0.7	1.00	1.28	1.56	1.84	2.12
0.8	1.00	1.28	1.56	1.84	2.12
0.9	1.00	1.28	1.56	1.84	2.12
1.0	1.00	1.28	1.56	1.84	2.12

fuel-consumption rate in gallons per mile shown in the table above for the normal freeway operating speed and that shown for the reduced work-zone speed multiplied by the traffic volume in vehicles per hour represents the amount of this fuel savings in gallons per hour per mile of work zone. This fuel saving over the range of work-zone V/C for the six lane-closure situations is shown in Figure 2.

Truck Fuel-Consumption Factors

To include the fuel consumption of trucks in the analysis of the effect of freeway work zones on fuel consumption, the factors presented in Tables 2 and 3 must be applied to the values obtained from Figures 1 and 2, respectively. The composite truck represented by the factors is an average of counts taken at four rural Interstate locations in Nebraska (5). The distribution of these trucks is as follows: 30.4 percent pickup and panel trucks, 8.2 percent two-axle six-tire trucks, and 61.4 percent tractor semitrailer truck combinations, of which 80 percent contain diesel engines. These percentages were divided into weight distributions so that the consumption tables presented by Claffey (4) could be used to calculate the fuel consumed by the composite truck.

The truck fuel-consumption factors in Tables 2 and 3 were computed by comparing the amount of fuel consumed with each percentage of trucks in the traffic stream to the amount of fuel consumed without any trucks in the traffic stream. The amount of fuel consumed per speed-change cycle for each combination of truck percentage and V/C was divided by the amount of fuel consumed per speed-change cycle for the corresponding V/C without trucks to obtain the factors in Table 2. Likewise, the amount of fuel consumed per hour per mile for each combination of truck percentage and V/C was divided by the amount of fuel consumed per hour per mile for the corresponding V/C without trucks to obtain the factors shown in Table 3. Thus, to adjust for trucks, an excess fuel-consumption value obtained from Figure 1 is multiplied by the appropriate factor in Table 2 and a fuel savings value obtained from Figure 2 is multiplied by the appropriate factor in Table 3.

OVERSATURATED CONDITIONS

As the demand volumes through a work zone increase, the V/C of the section also increases. Assuming uniform arrivals, a queue begins to form when V/C exceeds one. At this point, the energy consumption increases dramatically due to two factors: (a) idling time in the queue and (b) additional speed-change cycles experienced by vehicles coming to a complete stop. Of course, as in the case of under-

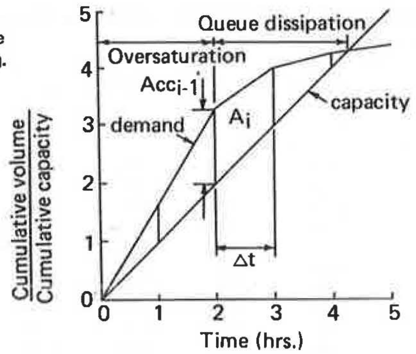


Figure 3. Graphical representation of queue forming and dissipating.

saturated conditions, there is a decrease in fuel consumption as a result of vehicles traversing the work zone at lower speeds. However, unlike undersaturated conditions, the algebraic sum of the effects of these three factors is nearly always positive, which indicates a net excess fuel consumption that results from freeway work zones during oversaturated traffic flow conditions.

Effect of Idling

Figure 3 is a plot of the cumulative V/C versus time for a hypothetical pattern of demand during oversaturation in a work zone. The area between the demand and the capacity V/C curves, multiplied by the capacity of the work zone, represents the total number of vehicle hours of idling time. The area between the demand and capacity V/C curves for any constant time increment during oversaturation when demand V/C is greater than one is as follows:

$$A_i = [(1/2)(V/C_i - 1)\Delta t + ACC_{i-1}]\Delta t \tag{4}$$

where

- A_i = area between the demand and capacity curves during the ith time increment (hours^2);
- V/C_i = volume-to-capacity ratio during the ith time increment;
- ACC_i = accumulation of demand over capacity during the ith time increment, which is equal to $(V/C_i - 1)\ \Delta t + ACC_{i-1}$ (hours); and
- Δt = constant time increment (hours).

At the end of periods of oversaturation, when the demand drops below the capacity (i.e., demand V/C is less than one), the queue will dissipate. The area between the demand and capacity V/C curves for any constant time increment during the dissipation of the queue is

$$A_i = [ACC_{i-1} - (1/2)(1 - V/C_i)\Delta t]\Delta t \tag{5}$$

The instant that the queue has dissipated does not necessarily occur at the end of a constant time increment. Therefore, the final triangular area between the demand and capacity V/C curves when the queue is dissipating is

$$A_n = [(1/2)(ACC_{n-1})^2]/(1 - V/C_n) \tag{6}$$

where n is the total number of hours during a period of oversaturation and queue dissipation divided by the constant time increment Δt plus one for any remainder. One is not added if there is no remainder.

The total idling time caused by oversaturation is as follows:

$$T = C \sum_{i=1}^{n} A_i \tag{7}$$

where T is the total idling time (vehicle-h) and C is the capacity of the work zone (vehicles/h).

Thus, the fuel consumed by vehicles idling in a queue is

$$F_I = Tg_i \tag{8}$$

where F_I is the fuel consumed by vehicles idling in queue (gal) and g_i is the fuel-consumption rate for i percent trucks (gal/h). Fuel-consumption rates for idling vehicles are presented in the table below. These values were derived from data presented by Claffey (4):

Trucks (%)	Fuel Consumed (gal/h)
0	0.58
10	0.57
20	0.57
30	0.56
40	0.56

Effect of Speed-Change Cycles During Queuing

During periods of oversaturation, speed-change cycles have a greater impact on fuel consumption because the vehicles must come to a complete stop as opposed to just reducing their operating speed. In reality, a vehicle must reduce its speed from the normal operating speed to zero, accelerate from zero to 30 mph (i.e., the operating speed in the work zone at capacity), and then accelerate from 30 mph back to the previous normal operating speed. This effect can be approximated by one speed-change cycle from normal operating speed to a complete stop.

The excess fuel consumed as a result of the stop-go cycles is calculated by the same method as for the speed-change cycles in the undersaturated case, except that the reduced speed is always zero. During a given time increment, the operating speed in the section without a lane closure can be found by using the idealized speed-volume relation previously discussed. The excess fuel consumed during a stop-go speed-change cycle at this operating speed can be determined from the table below, which was derived from data presented by Claffey (4) (note, data are for the composite passenger car representative of the following vehicle distribution: 20 percent large cars, 65 percent standard cars, 10 percent compact cars, and 5 percent small cars):

Speed (mph)	Fuel Consumed (gal)
10	0.0016
20	0.0066
30	0.0097
40	0.0128
50	0.0168
60	0.0208
70	0.0243

The values from this table multiplied by the hourly volume during the time increment provide the excess fuel consumed per time increment due to stop-go cycles caused by the presence of a queue that results from oversaturation during the time increment, as follows:

$$f_{si} = g_{si} V_i \Delta t \tag{9}$$

where

- f_{si} = excess fuel consumed due to stop-go speed-change cycles during ith time increment (gal),

Figure 4. Excess fuel consumption due to speed-change cycles during oversaturation.

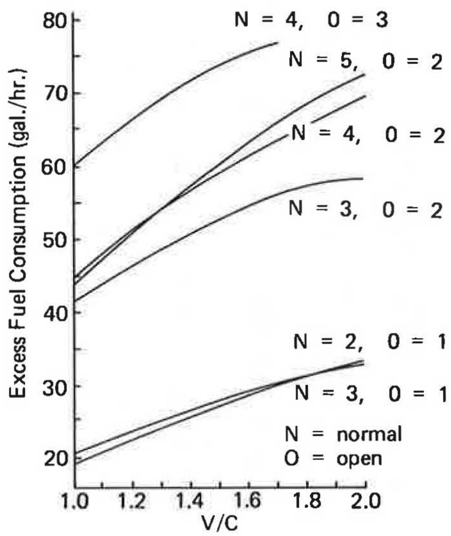
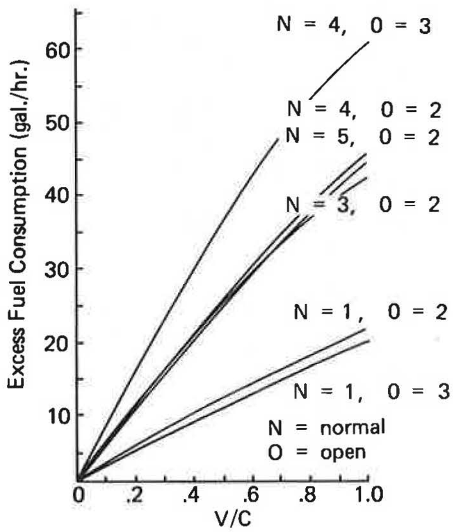


Figure 5. Excess fuel consumption due to speed-change cycles during queue dissipation.



g_{si} = excess fuel consumed per stop-go speed-cycle change during ith time increment (gal), and

V_i = hourly flow rate during ith time increment (vehicles/h).

Figure 4 shows the excess fuel consumed per hour by stop-go speed-change cycles during oversaturation on the six lane-closure situations considered in this study. Figure 5 shows the excess fuel consumed per hour by stop-go speed-change cycles while the queue caused by oversaturation is dissipating.

As discussed in the previous section, the instant that the queue has dissipated does not necessarily occur at the end of a constant time increment. Therefore, the excess fuel consumed due to stop-go speed-change cycles during the final time increment is as follows:

$$f_{sn} = g_{sn} V_n \Delta t \, [ACC_{n-1}/(1 - V/C_n)] \tag{10}$$

where n is the total number of hours during a period of oversaturation and queue dissipation divided by the constant time increment Δt plus one for any remainder. One is not added if there is no remainder.

Thus, the total excess fuel consumed due to stop-go speed-change cycles during a period of oversaturation and queue dissipation is

$$F_s = \sum_{i=1}^{n} f_{si} \tag{11}$$

where F_s is the excess fuel consumed due to stop-go speed-change cycles during period oversaturation and queue dissipation (gal).

Effect of Reduced Speed Operation During Queuing

It is assumed that the speed of operation through a construction work zone when a queue is present is 30 mph. This means that the fuel savings realized as a result of a lower operating speed can be determined by the same method as for the undersaturated case, except that the reduced speed is always 30 mph.

For a given volume, the operating speed in the section with all lanes open is calculated and the fuel-consumption rate per mile is read from the in-text table in the section on Effect of Reduced Operating Speed. The fuel-consumption rate per mile at 30 mph is subtracted from this value to find the fuel saved per vehicle per mile of the work zone. Figure 6 shows this fuel savings during oversaturation on the six lane-closure situations considered in this study. Figure 7 shows this fuel savings while the queue caused by oversaturation is dissipating.

Truck Fuel-Consumption Factors

The truck adjustment factors found in Tables 4 and 5 were developed and applied in the same manner as the tables for undersaturated conditions. The V/C during a given time increment, along with the percentage of trucks, is used to determine the factor to be applied to the fuel consumption for the composite car. Table 4 contains adjustment factors for fuel consumption due to stop-go speed-change cycles, and Table 5 contains the adjustment factors for the change in consumption due to the reduced speed in a work zone.

EXAMPLE PROBLEM

The following example illustrates the procedure used to determine excess fuel consumption. The volumes used were taken from actual data collected at a continuous traffic count location in the eastbound lane of Interstate 80 east of 42nd Street in Omaha, Nebraska (5). This section is a tangent three-lane roadway with high-type pavement.

Table 6 is a summary of the computations that were done to estimate the excess fuel consumption due to the closing of one lane for maintenance work. The length of the lane closure is 1 mile.

Columns 1 and 2 give the hour of the day and its respective volume. The V/C's of the section with all lanes open and with one lane closed are shown in columns 3 and 4. These were obtained by dividing the volume from column 2 by the capacities for this lane-closure condition (data from in-text table in section on Effect of Speed-Change Cycles).

To compute the values in column 5, column 4 is scanned to locate V/C's greater than 1.0. In this example, there are two periods of oversaturation: 7:00-9:00 a.m. and 4:00-5:00 p.m. Columns 5 and 6 can be computed by using equations for oversaturated conditions. For example, Equation 5 gives the area value for the period between 9:00 and 10:00 a.m., i.e.,

Figure 6. Fuel savings due to speed reduction during oversaturation.

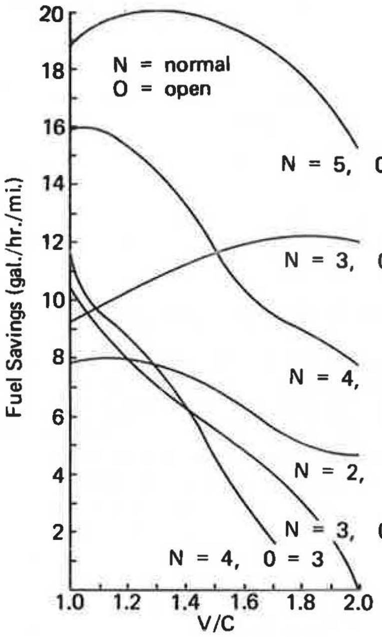
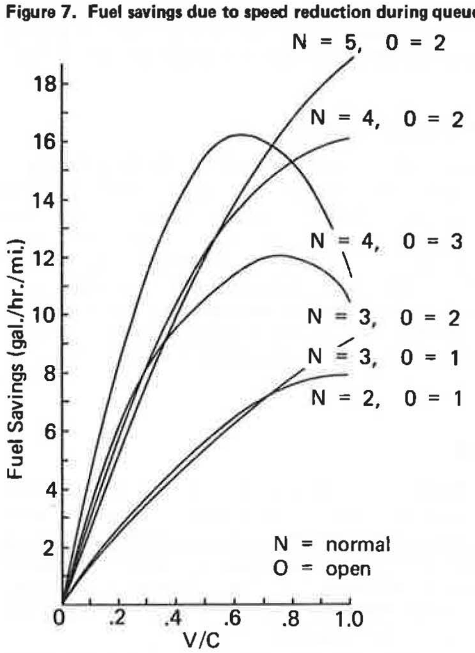


Figure 7. Fuel savings due to speed reduction during queue dissipation.



$$A = [0.39 - (1/2)(1 - 0.70)(1)] = 0.24\ h^2 \quad (12)$$

The accumulator value is as follows:

$$ACC = (0.70 - 1.0)(1) + 0.39 = 0.09\ h \quad (13)$$

During the period between 10:00 and 11:00 a.m., the accumulator value for the previous hour (0.09) is less than the V/C subtracted from 1.0 (0.35). This means that the queue is dissipating during this hour. The area value for this hour is calculated by using Equation 6:

$$A = [(1/2)(0.09)^2]/(1 - 0.65) = 0.01\ h^2 \quad (14)$$

The remainder of column 5 is computed in the same manner.

Table 4. Truck factors for fuel consumption due to stop-go speed-change cycles—oversaturated conditions.

	Truck Factors at Following Percentages						
V/C	0	5	10	15	20	30	40
0.1	1.00	1.25	1.50	1.75	2.00	2.50	3.00
0.2	1.00	1.25	1.50	1.75	2.00	2.50	3.00
0.3	1.00	1.25	1.49	1.74	1.98	2.47	2.96
0.4	1.00	1.24	1.48	1.72	1.96	2.44	2.92
0.5	1.00	1.24	1.48	1.72	1.96	2.44	2.92
0.6	1.00	1.24	1.47	1.71	1.94	2.41	2.88
0.7	1.00	1.23	1.46	1.69	1.92	2.38	2.84
0.8	1.00	1.23	1.46	1.69	1.92	2.38	2.84
0.9	1.00	1.23	1.46	1.69	1.92	2.38	2.84
1.0	1.00	1.23	1.45	1.68	1.90	2.35	2.80
1.1	1.00	1.22	1.43	1.65	1.86	2.29	2.72
1.2	1.00	1.22	1.43	1.65	1.86	2.29	2.72
1.3	1.00	1.21	1.42	1.63	1.84	2.26	2.68
1.4	1.00	1.21	1.41	1.62	1.82	2.23	2.64
1.5	1.00	1.20	1.40	1.60	1.80	2.20	2.60
1.6	1.00	1.20	1.40	1.60	1.80	2.20	2.60
1.7	1.00	1.20	1.40	1.60	1.80	2.20	2.60
1.8	1.00	1.20	1.39	1.59	1.78	2.17	2.56
1.9	1.00	1.19	1.38	1.57	1.78	2.14	2.56
2.0	1.00	1.19	1.38	1.57	1.76	2.14	2.52

Table 5. Truck factors for fuel consumption as affected by speed—oversaturated conditions.

	Truck Factors at Following Percentages						
V/C	0	5	10	15	20	30	40
0.1	1.00	1.17	1.33	1.50	1.66	1.99	2.32
0.2	1.00	1.16	1.32	1.48	1.64	1.96	2.28
0.3	1.00	1.16	1.32	1.48	1.64	1.96	2.28
0.4	1.00	1.16	1.31	1.47	1.62	1.93	2.24
0.5	1.00	1.15	1.30	1.45	1.60	1.90	2.20
0.6	1.00	1.15	1.29	1.44	1.58	1.87	2.16
0.7	1.00	1.15	1.29	1.44	1.58	1.87	2.16
0.8	1.00	1.15	1.29	1.44	1.58	1.87	2.16
0.9	1.00	1.15	1.29	1.44	1.58	1.87	2.16
1.0	1.00	1.14	1.28	1.42	1.56	1.84	2.12
1.1	1.00	1.13	1.26	1.39	1.52	1.78	2.04
1.2	1.00	1.16	1.31	1.47	1.62	1.93	2.24
1.3	1.00	1.11	1.21	1.32	1.42	1.63	1.84
1.4	1.00	1.14	1.27	1.41	1.54	1.81	2.08
1.5	1.00	1.09	1.18	1.27	1.36	1.54	1.72
1.6	1.00	1.13	1.26	1.39	1.52	1.78	2.04
1.7	1.00	1.09	1.17	1.26	1.34	1.51	1.68
1.8	1.00	1.12	1.23	1.35	1.46	1.69	1.92
1.9	1.00	1.15	1.29	1.44	1.58	1.87	2.16
2.0	1.00	1.16	1.31	1.47	1.62	1.93	2.24

Column 7 is obtained directly from the appropriate figure by using the V/C from column 4. If no queue is present, Figure 1 is used. If a queue is present, a value will appear in column 5, and Figure 4 or 5 should be used instead.

At the end of the queuing period, the consumption value for column 7 is computed as the weighted average of the values obtained from the undersaturated and the oversaturated cases. The weighting factor (wf) for the hour from 10:00 to 11:00 a.m. would be

$$wf = 0.09/(1 - 0.65) = 0.275 \quad (15)$$

By using this weighting factor, the value for column 7 is obtained from the appropriate values found in Figures 1 and 5 at a V/C of 0.65, i.e.,

$$f_{sn} = 0.257 \times 30.3 + (1 - 0.257) \times 6.5 = 12.6 \quad (16)$$

Column 8 is obtained by using the procedure outlined above and Figures 2, 6, and 7.

The excess fuel consumption for the entire day is

Table 6. Example problem computations.

(1) Hour	(2) Volume (vehicles/h)	(3) Normal V/C	(4) Work-Zone V/C	(5) A (h^2)	(6) ACC (h)	(7) Fuel Excess (gal/h)	(8) Fuel Savings (gal/h)
12:00-1:00 a.m.	580	0.10	0.19	0	0	0.6	0.6
1:00-2:00 a.m.	334	0.06	0.11	0	0	0.2	0.2
2:00-3:00 a.m.	201	0.03	0.07	0	0	0.1	0.1
3:00-4:00 a.m.	169	0.03	0.06	0	0	0.1	0
4:00-5:00 a.m.	234	0.04	0.08	0	0	0.1	0.1
5:00-6:00 a.m.	467	0.08	0.16	0	0	0.4	0.5
6:00-7:00 a.m.	1845	0.31	0.62	0	0	5.9	8.2
7:00-8:00 a.m.	4173	0.70	1.39	0.20	0.39	50.2	6.4
8:00-9:00 a.m.	2997	0.50	1.00	0.39	0.39	41.4	10.5
9:00-10:00 a.m.	2091	0.35	0.70	0.24	0.09	32.1	12.0
10:00-11:00 a.m.	1950	0.33	0.65	0.01	0	12.6	9.4
11:00-12:00 a.m.	2071	0.35	0.69	0	0	7.2	8.9
12:00-1:00 p.m.	2022	0.34	0.67	0	0	6.9	8.7
1:00-2:00 p.m.	2200	0.37	0.73	0	0	7.9	9.2
2:00-3:00 p.m.	2308	0.38	0.77	0	0	8.9	9.5
3:00-4:00 p.m.	2763	0.46	0.92	-	-	12.2	10.3
4:00-5:00 p.m.	3094	0.52	1.03	0.02	0.03	21.1	10.0
5:00-6:00 p.m.	2635	0.44	0.88	0	0	10.5	10.6
6:00-7:00 p.m.	1998	0.33	0.67	0	0	6.9	8.7
7:00-8:00 p.m.	1692	0.28	0.56	0	0	4.9	7.3
8:00-9:00 p.m.	1305	0.22	0.44	0	0	3.1	4.2
9:00-10:00 p.m.	1225	0.20	0.41	0	0	2.7	3.5
10:00-11:00 p.m.	1043	0.17	0.35	0	0	2.0	2.5
11:00-12:00 p.m.	878	0.15	0.29	0	0	1.4	1.6
Total				0.86		239.4	143.0

obtained from the sum of columns 5, 7, and 8. The sum of column 8 is multiplied by the capacity of the work zone and the idling consumption rate found in Table 5. Thus, the excess fuel consumption due to idling is

$$0.84\ h^2 \times (3000\ \text{vehicles/h}) \times (0.58\ \text{gal/h}) = 1462\ \text{gal} \quad (17)$$

The sum of column 7 gives the amount of excess fuel consumed due to speed-change cycles. This value is 239.4 gal. The decrease in fuel consumption caused by reduced-speed operation through the work zone (143.0 gal) is given by the sum of column 8.

The combined effect of all factors results in a net increase in fuel consumption of

$$1462\ \text{gal} + 239\ \text{gal} - 143\ \text{gal} = 1558\ \text{gal} \quad (18)$$

CONCLUSIONS

The procedure developed and demonstrated in this paper can be used in planning and scheduling freeway work zones to estimate the effect of lane closures on fuel consumption. The graphs presented can be used to facilitate the application of the procedure to the following lane-closure situations:

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

However, in using the tables and graphs presented in this paper, it should be noted that they are based on composite vehicles derived from specific vehicle distributions and data presented by Claffey (4). Therefore, if it is determined that these composite vehicles are not acceptable for a particular situation, appropriate adjustment factors should be applied to the values obtained from these tables and figures when using the procedure.

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