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# Mobile Source Emissions and Energy Analysis at an Isolated Intersection

DANE ISMART

**A simplified technique is presented for evaluating the effect improvements will have on mobile source emissions and energy use at an isolated intersection. The procedure relates emissions of CO, HC, and $NO_x$ and energy analysis to traffic-flow conditions at an intersection. A level of service is determined by using the critical movement analysis technique. By use of empirical data from a Federal Highway Administration report, stopped delay per vehicle is converted to the number of vehicles idling, slowing down, and stopping. Based on an NCHRP project, stopped delay per vehicle is related to level of service. The change from a base condition in idling time and vehicles stopping and slowing down as a result of an intersection improvement is used as the basis for determining the total reduction in pollutant emissions and energy use. The reductions are stated in terms of pounds and gallons as well as percentage reduction from the base condition. The procedure is designed to be a sketch planning tool for planners in small urbanized areas who have limited technical resources and data. The information necessary to use the procedure includes (a) total traffic entering the intersection, (b) turning movements, (c) number of approach lanes, (d) exclusive-use lanes, (e) approach speed, and (f) an estimate of the average upstream and downstream distance from the intersection where vehicle speeds are affected.**

The procedure described in this paper will relate the emissions of air pollutants and energy to traffic-flow conditions at an isolated intersection. Traffic flow will be analyzed under the following classifications:

1. "Idling"--Vehicle hours of stopped delay,
2. "Slowdowns"--Total number of speed changes, and
3. "Stopping"--Total number of vehicles stopping.

By determining the changes in the number of vehicles idling, slowing down, and stopping, and by applying appropriate energy and emission rates, it will be possible to estimate the reduction in energy use and pollutants emitted as a result of the improvement of traffic operations at an intersection.

## ENERGY USE AND EMISSION RATES

The table below (1) indicates fuel consumed and pollutant emissions for every 1000 vehicle-h of idling (January 1975 conditions for fuel consumption):

| Item | Amount per 1000 Vehicle Hours |
|---|---|
| Gasoline (gal) | 650 |
| Pollutants (lb) | |
| Carbon monoxide (CO) | 2430 |
| Hydrocarbon (HC) | 160 |
| Nitrogen oxides ($NO_x$) | 50 |

Figure 1 shows the additional fuel consumed for 1000 speed changes for various speeds [fuel consumption rates prevailing in January 1975 (2)]. This graph is used to determine the additional fuel consumed by vehicles that slow down as they approach an intersection. As a driver approaches an intersection, he will slow down his vehicle if there is a queue or if the light he approaches is in a red phase. If the queue dissipates or the signal changes before the vehicle reaches the intersection, the driver may only slow down and then return to his original speed. Figure 1 determines the additional fuel consumed based on this type of speed change.

For vehicles that stop completely, Figure 1 can also be applied. In this case, a stopped vehicle would be considered as going from the initial speed to 0 mph and then returning to the initial speed.

Figures 2-4 indicate the CO, HC, and $NO_x$ emissions per 1000 speed changes. As was the case for fuel consumption, these figures can be applied for vehicles that slow down and stop.

Figure 1. Additional fuel consumption for vehicle speed changes beyond consumption caused by continuing at uniform speed.

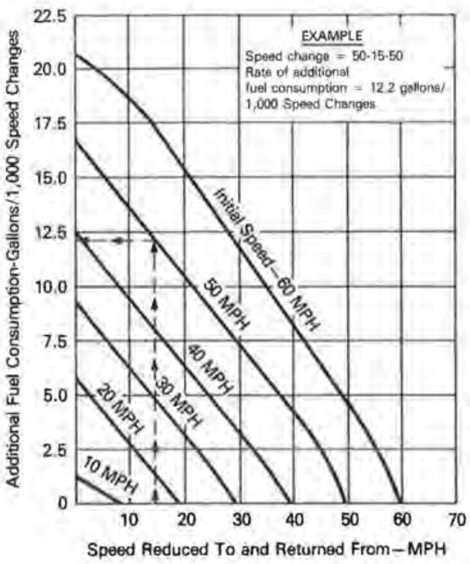



Figure 2. CO emissions for vehicle speed changes.

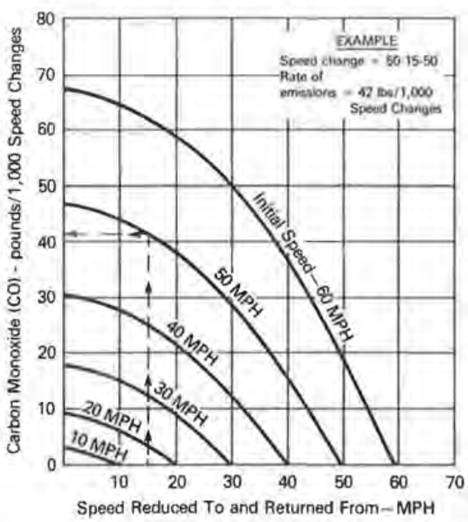



Figure 3. HC emissions for vehicle speed changes.

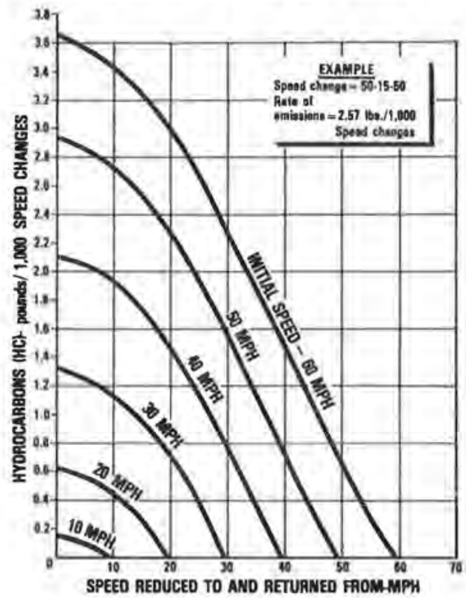
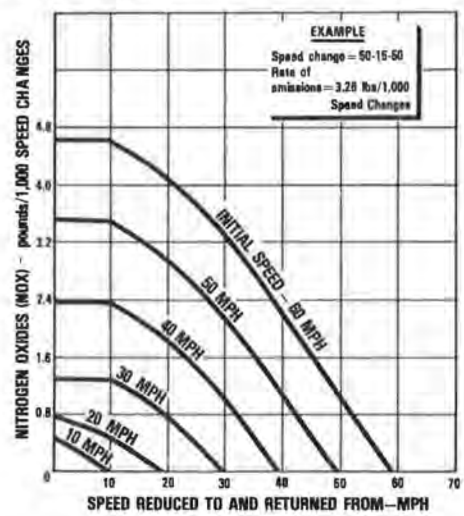



Figure 4. $NO_x$ emissions for vehicle speed changes.




TRAFFIC-FLOW CHARACTERISTICS

In order to evaluate proposed intersection improvements, changes in traffic flow must be analyzed. The general strategy for this evaluation is to relate level of service to stopped delay per vehicle. Changes in idling, slowdowns, and stopping are based on stopped delay per vehicle.

The following relations were developed empirically from a Federal Highway Administration (FHWA) report (3).

Stopping

$$\text{Percent stopping} = 0.5497 \log_{10} (\text{ADPV}) - 0.1404 \quad (1)$$

$$\text{ADPV} = 1.3 \times \text{SDPV} \quad (2)$$

where ADPV is approach delay per vehicle (approach delay divided by the total number of vehicles passing through the intersection approach during a period of time, in vehicle seconds per vehicle) and SDPV is stopped delay per vehicle (stopped delay divided by the total number of vehicles passing through the intersection approach during a period of time, in vehicle seconds per vehicle).

Substituting SDPV for ADPV yields

$$\text{Percent stopping} = 0.5497 \log_{10} (0.3 \times \text{SDPV}) - 0.1404 \quad (3)$$

To determine the number of vehicles stopping, multiply percent stopping times the total traffic entering the intersection (TTEI) for a specific time period:

$$\text{Number of stopped vehicles} = [0.5497 \log_{10} (\text{SDPV} \times 1.3) - 0.1404] \times \text{TTEI} \quad (4)$$

To determine additional fuel consumption due to stopping, multiply the number of stopped vehicles times the additional fuel consumption rate (FCR) per speed change. The rate is obtained from Figure 1 by dividing by 1000. This will convert the rate from gallons per 1000 speed changes to gallons per speed

Table 1. Excess hours consumed per speed-change cycle beyond hours consumed by continuing at initial speed (for passenger cars).

| Initial Speed (mph) | Speed Reduced To and Returned From (mph) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stop | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| 5 | 1.02 | | | | | | | | | | |
| 10 | 1.51 | 0.62 | | | | | | | | | |
| 15 | 2.00 | 1.12 | 0.46 | | | | | | | | |
| 20 | 2.49 | 1.62 | 0.93 | 0.35 | | | | | | | |
| 25 | 2.98 | 2.11 | 1.40 | 0.80 | 0.28 | | | | | | |
| 30 | 3.46 | 2.60 | 1.87 | 1.24 | 0.70 | 0.23 | | | | | |
| 35 | 3.94 | 3.09 | 2.34 | 1.69 | 1.11 | 0.60 | 0.19 | | | | |
| 40 | 4.42 | 3.58 | 2.81 | 2.13 | 1.52 | 0.97 | 0.51 | 0.16 | | | |
| 45 | 4.90 | 4.06 | 3.28 | 2.57 | 1.93 | 1.34 | 0.83 | 0.42 | 0.13 | | |
| 50 | 5.37 | 4.54 | 3.75 | 3.01 | 2.34 | 1.71 | 1.15 | 0.68 | 0.35 | 0.11 | |
| 55 | 5.84 | 5.02 | 4.21 | 3.45 | 2.74 | 2.08 | 1.47 | 0.94 | 0.57 | 0.28 | 0.09 |

change. The equation then becomes

$$\text{Additional fuel (gal)} = [0.5497 \log(\text{SDPV} \times 1.3) - 0.1404] \times \text{TTEI} \times [\text{FCR (Figure 1)}/1000] \quad (5)$$

For pollutant emissions due to stopping, the number of stopped vehicles is multiplied by the emission rates for HC, CO, and $NO_x$ per speed change. The rates are obtained from Figures 2, 3, and 4--i.e., by dividing by 1000 to convert the rates from pounds per 1000 speed changes to pounds per speed change. The equations for pollutant emissions (in pounds) due to stopping become

$$\text{CO} = [0.5497 \log_{10}(\text{SDPV} \times 1.3) - 0.1404] \times \text{TTEI} \times [\text{ER (Figure 2)}/1000] \quad (6)$$

$$\text{HC} = [0.5497 \log_{10}(\text{SDPV} \times 1.3) - 0.1404] \times \text{TTEI} \times [\text{ER (Figure 3)}/1000] \quad (7)$$

$$NO_x = [0.5497 \log_{10}(\text{SDPV} \times 1.3) - 0.1404] \times \text{TTEI} \times [\text{ER (Figure 4)}/1000] \quad (8)$$

Slowdowns

To determine the time lost due to vehicles slowing down but not stopping, the following equation is used:

$$\text{Slowdown delay} = \text{total approach delay} = \text{time in queue delay} \quad (9)$$

From FHWA (3),

$$\text{Time in queue delay} = (\text{stopped delay per stopped vehicle} - 11.33)/0.76 \quad (11)$$

$$\text{Total approach delay} = 1.3 \times \text{SDPV} \times \text{TTEI} \quad (10)$$

$$\text{Stopped delay per stopped vehicle} = 0.96\,(\text{SDPV}) + 11.10 \quad (12)$$

Substituting Equation 9 for SDPV in Equation 8,

$$\text{Time in queue} = \{[0.96\,(\text{SDPV}) + 11.10 - 11.33]/0.76\} \times \text{TTEI} \quad (13)$$

$$\begin{aligned}\text{Slowdown delay} &= \text{TTEI} \times 1.3 \times \text{SDPV} - \{[0.96\,(\text{SDPV}) - 0.23]/0.76\} \times \text{TTEI} = \text{TTEI} \times 1.3 \times \text{SDPV} \\ &\quad - [1.26\,(\text{SDPV}) - 0.30] \times \text{TTEI} = 1.3 \times \text{TTEI} \times \text{SDPV} - 1.26 \times \text{TTEI} \times \text{SDPV} \\ &\quad + 0.30\ \text{TTEI} = \text{TTEI} \times (0.04\ \text{SDPV} + 0.30)\end{aligned} \quad (14)$$

To convert the slowdown delay in seconds to the number of vehicles slowing down in units of 1000, divide the slowdown delay by the excess hours consumed per 1000 speed-change cycles from Table 1 (4):

$$\text{Slowdowns per 1000 speed changes} = [\text{TTEI} \times (0.04\ \text{SDPV} + 0.30)]/[3600 \times \text{hours per 1000 speed changes (Table 1)}] \quad (15)$$

To determine excess energy consumption and emissions due to slowdowns at an intersection, multiply Equation 15 by the FCR and the emission rates (ERs) from Figures 1, 2, 3, and 4. The final forms of the equations for slowdowns are as follows (hours per speed change obtained from Table 1):

$$\text{Excess fuel consumption (gal)} = [\text{TTEI} \times (0.04\ \text{SDPV} + 0.30)]/(3600 \times \text{hours per 1000 speed changes}) \times \text{FCR (Figure 1)} \quad (16)$$

$$\text{CO (lb)} = [\text{TTEI} \times (0.04\ \text{SDPV} + 0.30)]/(3600 \times \text{hours per 1000 speed changes}) \times \text{ER (Figure 2)} \quad (17)$$

$$\text{HC (lb)} = [\text{TTEI} \times (0.04\ \text{SDPV} + 0.30)]/(3600 \times \text{hours per 1000 speed changes}) \times \text{ER (Figure 3)} \quad (18)$$

$$NO_x\ \text{(lb)} = [\text{TTEI} \times (0.04\ \text{SDPV} + 0.30)]/(3600 \times \text{hours per 1000 speed changes}) \times \text{ER (Figure 4)} \quad (19)$$

Idling

Fuel consumption and emissions due to idling can be computed by multiplying the number of vehicles entering the intersection by the stopped delay per vehicle times the rates given in the text table at the beginning of this paper. The equations for idling would be as follows:

$$\text{Energy (gal)} = (\text{TTEI}/3600) \times \text{SDPV} \times 0.65\ \text{gal} \quad (20)$$

$$\text{CO (lb)} = (\text{TTEI}/3600) \times \text{SDPV} \times 2.43\ \text{lb} \quad (21)$$

$$\text{HC (lb)} = (\text{TTEI}/3600) \times \text{SDPV} \times 0.16\ \text{lb} \quad (22)$$

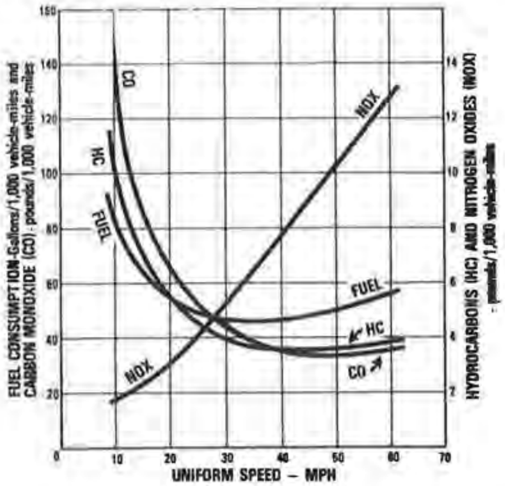
$$NO_x\ \text{(lb)} = (\text{TTEI}/3600) \times \text{SDPV} \times 0.05\ \text{lb} \quad (23)$$

## IMPLEMENTATION STRATEGY

The equations developed for determining energy use and vehicle emissions are based on stopped delay per vehicle. In the following table from NCHRP Project 3-28 (based on a synthesis of various data), stopped delay can be related to level of service: (V/C = volume/capacity)

| Level of Service | Typical V/C Ratio | Delay Range (s/vehicle) |
|---|---|---|
| A | 0.00-0.60 | 0.0-16.0 |
| B | 0.61-0.70 | 16.1-22.0 |
| C | 0.71-0.80 | 22.1-28.0 |
| D | 0.81-0.90 | 28.1-35.0 |
| E | 0.91-1.00 | 35.1-40.0 |
| F | Varies | >40.1 |

Figure 5. Fuel consumption and emissions of CO, HC, and $NO_x$ from driving 1000 miles at various uniform speeds.




[Delay range is measured as stopped delay (3). Delay values relate to the mean stopped delay incurred by all vehicles entering the intersection. Note that traffic-signal coordination effects are not considered and could drastically alter the delay range for a given V/C ratio.] By relating level of service to stopped delay per vehicle, the equations in this paper could be used to analyze vehicle emissions and energy. The technique would be most applicable in determining what effect an intersection improvement, such as constructing a left-turn lane, will have on energy consumption and air pollutant emissions.

The first step in the process is to determine the level of service by using the critical movement technique (4) for both the existing intersection and the intersection with the proposed improvement. The level of service would be correlated with the stopped delay from the table above. For example, from the critical movement technique it can be determined that an existing intersection has a level of service C and a critical intersection volume of 1100. The table below (1) gives intersection capacity by level of service for the critical movement technique (* indicates a special case):

| Level of Service | Capacity Range (vehicles/h) Low | High |
|---|---|---|
| A | 0 | 900 |
| B | 901 | 1050 |
| C | 1051 | 1200 |
| D | 1201 | 1350 |
| E | 1351 | 1500 |
| F | -* | 1500 |

Level of service C has a capacity range of 1051-1200 for the critical movement technique, and the preceding table indicates that level of service C has a stopped-delay range of 16.1-22 s/vehicle. Therefore, prorating the level of service, the delay for the existing intersection would be calculated as follows:

$(1100 - 1051)/(1200 - 1051) = (X - 16.1)/(22 - 16.1)$
where X = SDPV.
$49/149 = (X - 16.1)/5.9.$
$149X = 2688.$
X = 18 s/vehicle.

The same process would be used to determine the SDPV with the proposed intersection improvement.

The second step in the process is to use the existing and improved intersection stopped-delay values in the energy and emission equations. For simplifying purposes, it is assumed that the average vehicle slowing down but not stopping will reduce its initial speed by one-half. If, for example, the initial approach speed for an intersection is 30 mph, the reduction for the average vehicle would be 15 mph. Approach speed is defined as the speed limit of the approach lanes to the intersection. By using Table 1, for this example, 1.24 excess hours would be consumed per 1000 speed-change cycles.

After the energy and vehicle emissions are computed, the third step would be to compare the results for the existing intersection with those for the improved intersection. The difference in the results between the existing and proposed intersections is the reduction in energy use and air-quality emissions (due to fewer vehicles stopping, slowing down, and idling).

## APPLICATION

Significant changes in energy use and vehicle emissions as a result of an intersection improvement will only occur with a change in the level of service. For an intersection at low volumes, there may be no difference in the level of service between the existing and the improved facility. Both facilities may operate at a high level of service with low volumes. Consequently, there would be little change in the percentage of vehicles stopping, idling, and slowing down.

The evaluation for an intersection should be broken into peak and nonpeak analysis periods. The analysis periods should be based on the intersection operating at the same level of service for the entire analysis period. If there is a significant difference in the level of service in the peak or nonpeak period, it may be necessary to break down the analysis into smaller time units. The minimum time period that can be analyzed is 1 h.

Another problem in any emissions and energy analysis is the change in vehicle characteristics. In the future, the fuel consumption and vehicle emission rates will change. To compensate for this change, the rates should be modified periodically.

In evaluating an existing versus improved intersection, the percentage reduction in fuel consumption and emissions, as well as the absolute values, should be considered. To compute the percentage reduction for fuel, determine the total amount of fuel consumed at the existing intersection. At this point it has been demonstrated how to calculate the additional fuel consumed due to speed changes and idling. For the speed changes, the fuel consumed is in addition to the fuel consumed for traversing the same distance at a uniform speed. To obtain the total amount of fuel consumed, use Figure 5 (2) and add the fuel consumption indicated for a uniform speed to the consumption for speed changes and idling.

In Figure 5, the uniform speed is cross-referenced with consumption in gallons per 1000 vehicle miles. The uniform speed would be the approach speed for the intersection. By entering into Figure 5 with a uniform speed, the consumption rate can be determined. This rate is multiplied by vehicle miles at the intersection in units of 1000 to estimate fuel consumption at a uniform speed for all vehicles entering the intersection. To determine vehicle miles, an estimate must be made of the distance upstream from the intersection, where vehicles are initially affected by the intersection, and the distance downstream, where they have recovered their original speed. Normally, this distance will vary depending on the characteristics of the intersection. A reasonable estimate must be obtained from an individual who is familiar with the intersection in question.

The equation for uniform-speed fuel consumption is as follows:

$$\text{Fuel (gal)} = (\text{TTEI}/1000) \times \text{FCR (Figure 5)} \times \text{intersection distance} \qquad (24)$$

After the uniform fuel consumption is added to

**Figure 6. Format for total and incremental fuel consumption.**

| INCREMENTAL FUEL CONSUMED | BASE | ALTERNATIVE | REDUCTION (GALLONS) |
|---|---|---|---|
| Stopping | | | |
| Slowdowns | | | |
| Idling | | | |
| Σ INCREMENTAL FUEL CONSUMED | | | Σ REDUCTION |
| Uniform Speed | | | |
| TOTAL FUEL CONSUMED | | | |

EQUATIONS

$$\text{Stopping (Gals.)} = [.5497 \text{ LOG}_{10} (\text{SDPV} \times 1.3) - .1404] \times \frac{\text{TTEI}}{1000} \times \text{FCR (Figure 1)} \qquad (5)$$

$$\text{Slowdowns (Gals.)} = \frac{\text{TTEI} \times (.04\ \text{SDPV} + .30)}{3600 \times \text{Hours/1000 speed changes (Table 2)}} \times \text{FCR (Figure 1)} \qquad (16)$$

$$\text{Idling (Gals.)} = \frac{\text{TTEI}}{3600} \times (\text{SDPV}) \times .65 \text{ Gals.} \qquad (20)$$

$$\text{Uniform Speed (Gals.)} = \frac{\text{TTEI}}{1000} \times \text{FCR (Figure 5)} \times \text{Intersection Distance} \qquad (24)$$

WHERE:

SDPV = Stop delay per average vehicle
TTEI = Total traffic entering intersections
FCR = Fuel consumption rate
Intersection Distance = Estimate of average total distance in miles, upsteam and downstream from the intersection (example .1 miles) where the average vehicle's free flow speed is affected.

**Figure 7. Format for sum and total incremental air-quality emissions.**

| | Base | Alternative | Reduction |
|---|---|---|---|
| CO (Pounds) | | | |
| Stopping | | | |
| Slowdowns | | | |
| Idling | | | |
| Uniform Speed | X | | |
| Sum | | | |
| HC (Pounds) | | | |
| Stopping | | | |
| Slowdowns | | | |
| Idling | | | |
| Uniform Speed | X | | |
| Sum | | | |
| NO (Pounds) | | | |
| Stopping | | | |
| Slowdowns | | | |
| Idling | | | |
| Uniform Speed | X | | |
| Sum | | | |

| Σ Reduction | |
|---|---|
| CO | |
| HC | |
| NO | |

the consumption due to speed changes and idling, total fuel consumed has been determined. This value, when calculated for an existing intersection, will be used as the base for determining the percentage reduction for a proposed improvement. For example, at an intersection 1000 gal are consumed. With the construction of a left-turn lane, 100 gal less will be consumed. Therefore, the left-turn bay will reduce consumption by 100/1000, or 10 percent.

For vehicle emissions, Figures 2-4 represent total emissions for vehicles changing speeds. To simplify the analysis, it is assumed that for existing intersections most vehicles will experience a speed change at the intersection. Thus, for congested intersections, the emissions for idling, stopping, and slowing down represent total emissions. Total emissions for the existing intersection would be used just as in the analysis of energy as a base to determine the percentage reduction.

In the case of an improved intersection, total emissions would include vehicles that do not experience a speed change. The number of vehicles that do not stop or slow down can be estimated by equating it to the reduction of vehicles stopping when an existing intersection is improved.

For example, if the addition of a left-turn bay reduced the percentage of vehicles stopping from 80 to 70 percent and 4000 vehicles entered the intersection during the analysis period, it would be estimated that 400 vehicles (10 percent x 4000) will experience little interference when traversing the intersection. Then, to determine vehicle miles, the number of free-flowing vehicles would be multiplied by the distance from the intersection where vehicle movement is affected. This would be the same distance estimated for the energy analysis.

From Figure 5, pollutant emissions in units of 1000 vehicle miles for vehicles traveling at a uniform speed can be obtained. These emission rates multiplied by vehicle miles would determine the emissions for uniform-speed vehicles. The equation is as follows:

$$\begin{aligned} CO, HC, NO_x = {} & (TTEI/1000) \times ER \text{ (Figure 5)} \times \text{intersection distance} \\ & \times \text{percent reduction of vehicles stopping} \end{aligned} \tag{25}$$

When these emissions are combined with emissions due to slowdowns, stopping, and idling, the total emissions for an improved intersection can be calculated.

## SUMMARY

The procedure described in this paper is designed as a sketch planning tool for planners. Whereas the critical movement technique is a sketch planning tool for analyzing capacity, this methodology is a tool for evaluating vehicle emissions and energy. It can be applied quickly and can provide reasonable estimates of reductions in energy use and vehicle emissions. The quick-response characteristics of the method are demonstrated by the limited amount of data necessary to do an evaluation.

To simplify the application of the technique, the equations given in this paper for pollutant emissions (Equations 9-11, 17-19, 21-23, and 24) and the formats shown in Figures 6 and 7 should be used.

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# Improved Demand Estimation for Rural Work Trips

YORGOS J. STEPHANEDES

**A critical review of the most widely accepted rural demand estimation models is performed. Based on data collected in two rural towns, a disaggregate specification for rural work-trip modal choice is proposed. The new model includes a set of socioeconomic and a set of policy-relevant variables and can be used for implementing a wide range of transportation policies to improve rural transit system performance. Model variables produce coefficients consistent with the notion, recently found in the literature, that rural commuters are more sensitive to fiscal variables than are urban commuters. Results from comparison tests suggest that demand prediction with the proposed specification is significantly (up to 88 percent) better than with the best of the existing models.**

The evaluation of rural transportation projects that operate with federal or state support has been considered an essential part of government-subsidized transportation programs during the past decade. Transportation policies that can improve the efficiency and effectiveness of rural transit operations have recently been proposed (1), and data on performance measures for evaluating such operations are now available (1-3) and are being compiled by a number of states (4,5). In response to a need for identifying transportation policies that can also enhance rural mobility and the need to determine whether such policies will, in time, cause changes in rural economic development, a project was recently initiated (6). An immediate need for a demand estimation specification to estimate work-trip modal choice was identified.

The major objective of this study is to determine the most reliable rural demand estimation model suitable for implementing level-of-service transportation policies and sensitive to long-term mobility and economic changes that may take place in a community. This determination depends on certain basic criteria: (a) the ability of the selected model to estimate modal choice for work trips directly, (b) inclusion of level-of-service independent variables for implementing transportation policies that can improve the efficiency and effectiveness of a transit system, (c) inclusion of mobility and socioeco-