A Methodology for Quantifying Urban Freeway Congestion

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Urban freeway congestion is a serious and growing national problem, one that is receiving increasing attention from transportation engineers, planners, and researchers as well as local, state, and national officials. When attempting to quantify this problem or evaluate alternative solutions for a single freeway or for an urban area, one finds that a convenient methodology to calculate urban freeway congestion parameters such as delay, excess fuel consumption, and user costs does not exist. A computerized methodology is described that was developed to quantify urban freeway congestion parameters on a national basis. This methodology was applied to a national computerized database, but could be easily used by local agencies because the required input data are minimal. The procedure can be applied to a single freeway segment or to several segments in an urban area. The methodology described in this paper forms the basis of a user-friendly microcomputer program for calculating urban freeway congestion.

Urban congestion is a serious and growing national problem, one that is receiving increasing attention from transportation engineers, planners, and researchers as well as local, state, and national officials. These professionals typically must evaluate several types of improvements for alleviating congestion on urban freeways, including widening, surveillance and control systems, ramp metering, incident management, motorist information systems, high-occupancy-vehicle (HOV) facilities, and low-cost geometric improvements. When trade-off analyses for these improvements are performed, a simplified methodology for calculating urban freeway congestion parameters would be useful.

To quantify the national problem of urban freeway congestion for both existing and future traffic levels and to analyze the aggregate impacts of various methods of solving the problem, an FHWA staff research study was initiated. One of the outputs of the study was a consolidated computerized methodology to quantify urban freeway congestion parameters such as delay, excess fuel consumption, and user costs. This methodology is the subject of this paper.

DATA REQUIREMENTS

For the study on which this paper is based, the Highway Performance Monitoring System (HPMS) database maintained by FHWA was used. The HPMS database contains detailed geometric, traffic, and other data for approximately 50 percent of the urban freeway mileage in the nation. The HPMS data can be used to represent the total urban freeway system through the use of appropriate expansion factors supplied by each state.

The HPMS data items actually used are those that are typically readily available through local highway or traffic engineering agencies. The data items required by the methodology are as follows:

1. Section length,
2. Number of lanes,
3. Annual average daily traffic (AADT),
4. *K*-factor (percentage of AADT occurring during peak hour),
5. Peak-hour directional factor,
6. Shoulder width,
7. Lane width, and
8. Percent trucks.

The first six items are required to use the methodology. The last two are required only if an estimate of the freeway section capacity is desired. If this estimate is not desired, a value of directional freeway capacity must be specified as an input data item. (Any potential users of the methodology in this paper who intend to use HPMS data should carefully check the HPMS sampling basis for their particular state before developing data for individual urbanized areas. This is because some states have elected the option permitted under HPMS of sampling all urbanized areas within the state as a group.)

METHODOLOGY

Figure 1 is a flowchart of the steps in the analysis program developed to quantify urban freeway congestion parameters. The program is written in FORTRAN IV and was structured to handle the large data requirements of quantifying the urban freeway congestion problem on a national scale. Each of the major steps in the analysis program and how it was developed are given in the following paragraphs.

After the totals for the various calculated parameters have been initialized, the input data described in the previous section are read. The section capacity is then estimated if a directional-hourly capacity is not provided as an input data item. Capacity is calculated as follows:

$$C = 2{,}000NWT$$

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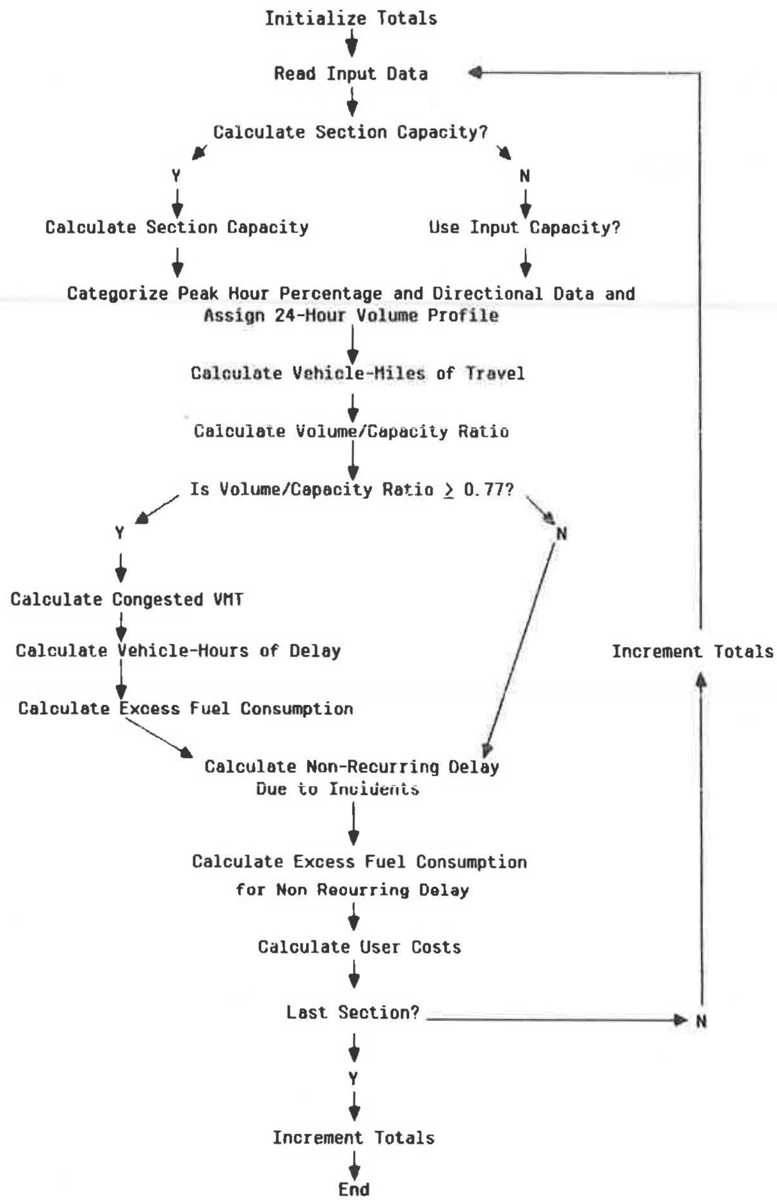

FIGURE 1 Steps in analysis program.

where

C = capacity,
N = number of lanes,
W = adjustment factor for lane width and lateral clearance, and
T = adjustment factor for truck presence based on percentage trucks and terrain.

Number of lanes is an input data item. The adjustment factor for lane width is approximated by using lane width and shoulder width (as a surrogate for distance to lateral obstructions) and the look-up tables in the 1985 *Highway Capacity Manual* (HCM) (*1*). The adjustment factor for trucks is also calculated by using the tables in the 1985 HCM. Percentage trucks is used directly and terrain is assumed to be basically level (two passenger-car equivalents per truck). Because the basic lane capacity in the foregoing equation is assumed to be 2,000 vehicles per lane per hour, design speed for the freeway is assumed to be at least 60 mph. The adjustment factor for population used in the 1985 HCM does not appear in this equation and is assumed to be 1.0 (commuter traffic) because the program applies only to urban freeways.

The next step in the analysis program is to assign a 24-hr volume profile to the freeway section. To simplify this process, several sets of traffic counts from I-66 and I-395 near Washington, D.C., were obtained. These counts, which were taken in 1983 and 1984 in various locations, represent a wide variety of peak-hour traffic percentages and directional factors. From them a total of twelve 24-hr volume profiles (expressed in terms of directional percentage of AADT) were developed for a "typical" urban freeway. The analysis program uses the input data for *K*-factor and directional factor to calculate a peak-hour directional percentage of AADT on the freeway section. An appropriate 24-hr volume profile is then selected on the basis of this percentage. The twelve 24-hr volume profiles developed are applicable for peak-hour directional percentages as low as 3.75 and as high as 9.25. The majority of urban freeway sections in the nation should fall into this range.

Total annual vehicle miles of travel is calculated next. This calculation is based entirely on input data. The equation for annual vehicle miles of travel for each section is given as follows:

$$VMT = AADT*LENGTH*365$$

where

VMT	=	total annual vehicle miles of travel,
AADT	=	annual average daily traffic,
LENGTH	=	expanded section length, and
365	=	days per year.

Before the calculations for annual congested vehicle miles of travel are performed, it is necessary to select a point at which congested flow begins. For the purposes of this methodology, it was decided to qualitatively define congestion as operation of the freeway under conditions where a typical motorist's trip would be significantly delayed compared with the same trip under low-volume conditions. The numerical values selected to describe this point were taken from the 1985 HCM (*1*), Table 3-1 of which gives density, average travel speed, volume/capacity ratio (*V/C*), and maximum service flow values for various levels of service. The point selected to define congestion was the boundary between levels-of-service C and D. At this point, the density is approximately 30 passenger cars per lane mile, average travel speed is approximately 54 mph, *V/C* is approximately 0.77, and maximum service flow is approximately 1,550 passenger cars per lane per hour for 70-mph design speed facilities. The values of speed and *V/C* were the two key parameters used as decision values in the analysis program. It should be noted here that the threshold point for congestion chosen for this study, the boundary between levels-of-service C and D, is qualitatively the same as that used in the U.S. Department of Transportation's reports to Congress on the status of the nation's highways (*2*) and AASHTO's recommended design standard for urban freeways (*1*). The values were based on the 1965 *Highway Capacity Manual* (*3*). In the analysis program, *V/C* is calculated for the freeway section for each hour of a typical day. If *V/C* is greater than or equal to 0.77, the flow on the section is considered to be congested and the travel occurring on the section during the hour is considered congested travel.

The formula for calculating total annual congested vehicle miles of travel is similar to the formula given earlier for total annual vehicle miles of travel:

$$CVMT = PCT*AADT*LENGTH*260$$

where

CVMT	=	total annual congested vehicle miles of travel,
PCT	=	percentage of daily traffic experiencing congested conditions, and
260	=	days per year when recurring congested conditions occur.

Following the calculation of congested vehicle miles of travel, the next step in the analysis program is to calculate annual vehicle delay due to recurring congestion. To perform this calculation, some assumptions were required for vehicle operating characteristics under both congested and uncongested conditions. First, it was assumed that the average travel speed under uncongested conditions (levels of service A-C) is 55 mph. This is probably a conservative estimate. For *V/C* between 0.77 and 1.00, average travel speed was estimated from the curves shown in Figure 3-4 of the 1985 HCM (reproduced here as Figure 2) (*1*). As shown in Figure 2, for 70-mph design facilities, average travel speed varies between 30 and 54 mph for *V/C* between 1.00 and 0.77. Finally, for *V/C* greater than 1.0 (representing level-of-service F) an average travel speed of 20 mph was assumed. Selection of this value was largely subjective, but is in close agreement with other values given in the literature (*4*).

Total annual delay due to recurring congestion is estimated by the following equation:

$$DELAY = (IDEAL - ACTUAL)*PCT*AADT*260$$

where

DELAY	=	annual delay due to recurring congestion,
IDEAL	=	ideal section travel time per vehicle (average speed, 55 mph), and
ACTUAL	=	actual section travel time per vehicle (less than ideal average speed).

This calculation is performed for each hour of congested travel on the freeway section.

Following the delay calculations, annual excess fuel consumption is calculated. A number of fuel consumption algorithms were studied to determine their applicability for use in this methodology. In particular, it was desired that an algorithm for the relationship between average speed and fuel consumption at congested freeway speeds be found, because average speed was already used in the analysis program for calculating delay. Unfortunately, current algorithms that describe this relationship apply only to speeds below 40 mph and are based on older vehicle fleets.

Therefore, a modified version of the fuel consumption data reported by Raus in 1981 (*5*) was used. In that study, fuel consumption values for average speeds between 1 and 35 mph were reported for the 1980 vehicle fleet. Data for average speeds between 20 and 35 mph were essentially linear. A linear regression best-fit analysis was applied to these data to determine an appropriate linear relationship that could be extended to average speeds up to 55 mph. The resulting expression is as follows:

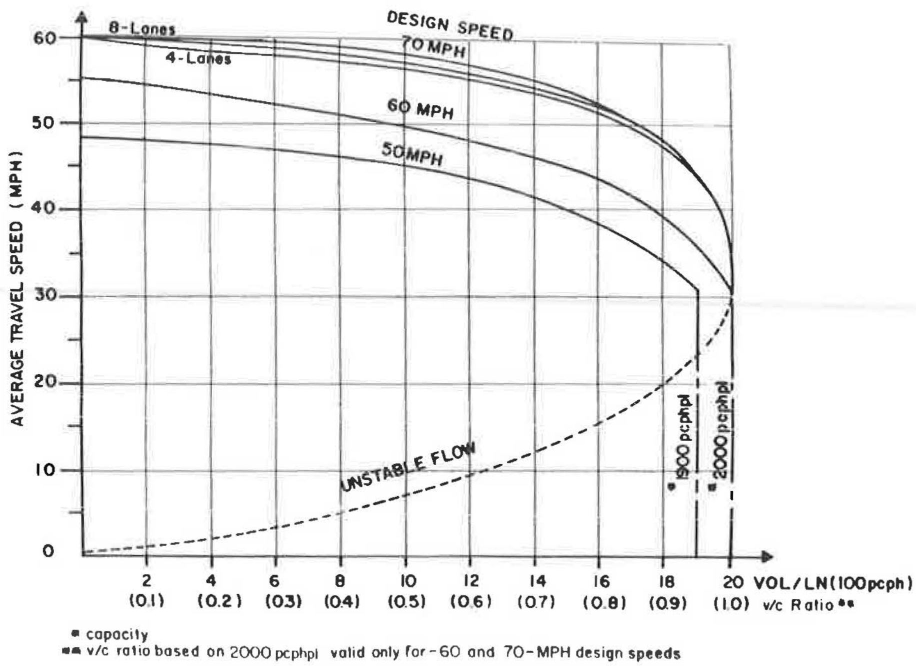

FIGURE 2 Speed-flow relationships under ideal conditions (*1*).

$$MPG = 8.8 + 0.25AVGSPD$$

where *MPG* is average fuel economy (in miles per gallon) and *AVGSPD* is average travel speed (in miles per hour).

Because this relationship is based on the 1980 passenger car vehicle fleet, fuel consumption estimates based on it may be slightly high. However, the presence of trucks in the traffic stream should tend to at least partially offset this potential error.

The next step in the analysis program is to estimate delay due to nonrecurring congestion caused by disabled vehicles and accidents. This portion of the methodology was based on previous work done on low-cost freeway incident management techniques (*6*). In this procedure, delay due to an incident can be estimated if information on freeway capacities and volumes and incident duration is known. The basic strategy was to apply the incident delay procedure repetitively for the freeway section for each hour of a typical day to estimate the total delay due to incidents.

This requires an average set of incident frequencies for various incident types, which was also available from the previous study on low-cost freeway incident management techniques. For the current methodology, two incident trees, one for freeways with adequate shoulders and one for freeways with no shoulders, were developed and are partially reproduced here as Figures 3 and 4. Each incident tree shows the breakdown by percentage of total incidents by incident type. Review of these figures indicates that a total of seven incident types were identified for freeways with adequate shoulders and five for freeways with no shoulders (by definition there can be no shoulder incidents on these facilities). The total incident rates associated with freeways with adequate shoulders and freeways with no shoulders are 200 and 79 incidents per million vehicle miles of travel, respectively. These incident frequencies were used directly in the analysis program.

As noted, freeway capacity under normal (nonincident) conditions either is an input data item or is calculated by the analysis program. Typical directional traffic volumes for each hour of the day are also derived as noted earlier. Freeway capacity during incident conditions, however, is not directly available and had to be derived. Figures for flow rates past one-lane incidents and shoulder accidents have been previously developed for typical four-, six-, and eight-lane freeways and are expressed in terms of vehicles per hour for typical capacity conditions (capacity = 1,850 vehicles/lane/hr) (*7*). For the analysis program, it was more useful to express these values in terms of percentage of total capacity remaining during an incident. It was also necessary to estimate values for shoulder disablements, two- and three-lane incidents, and freeway cross sections for up to 16 lanes. The final values used are shown in Table 1.

The average duration for incidents, including figures for both in-lane time and time spent on the shoulder, was estimated from several data sources on the basis of actual detection, response, and clearance times from operating urban freeways (*6-8*). These values are shown in Tables 2 and 3. Because the values shown in these tables are averages for each incident type, they are used in the analysis program each time an incident of that type occurs.

The overall operation of the incident delay portion of the analysis program includes (a) calculation of the number of occurrences per year for each incident type for each hour of the day using the incident trees shown in Figures 3 and 4, (b) calculation of the time until normal flow resumes following an incident by using freeway capacity and traffic volume information and the values in Tables 1-3, and (c) calculation of delay caused by the presence of an incident for each

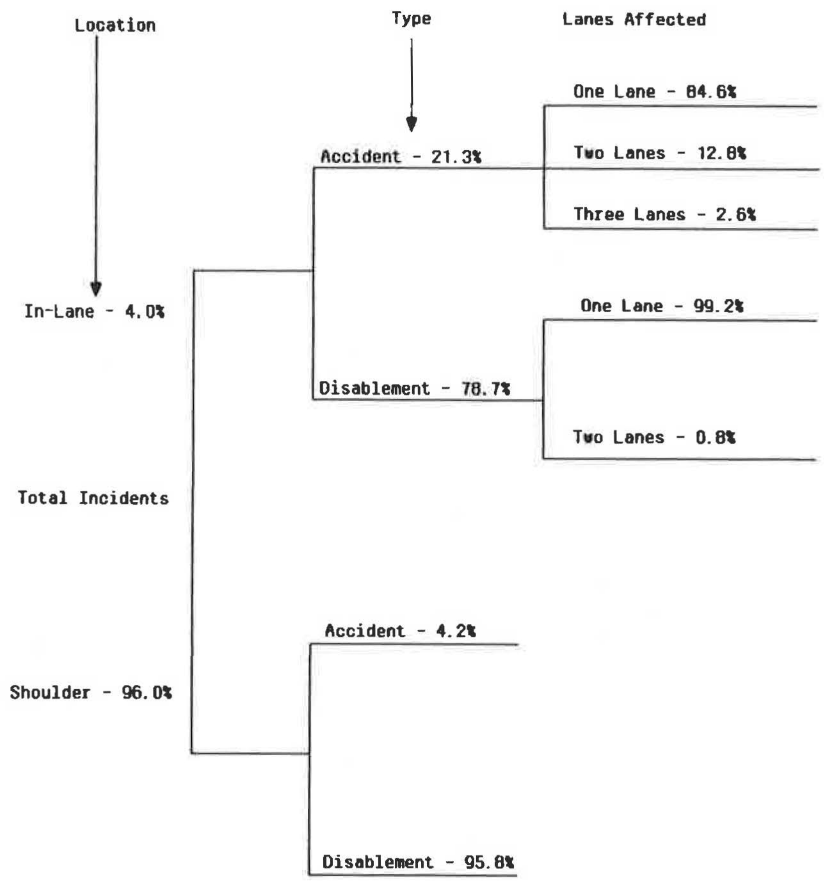

FIGURE 3 General incident tree (adequate shoulders).

incident type. Delay calculations are then expanded from a single incident occurrence to a full year by multiplying by the number of annual occurrences. A final step in the incident delay portion of the analysis program is to subtract from the incident delay total any recurring delay that would otherwise occur while the incident is present, to prevent double counting of the recurring delay.

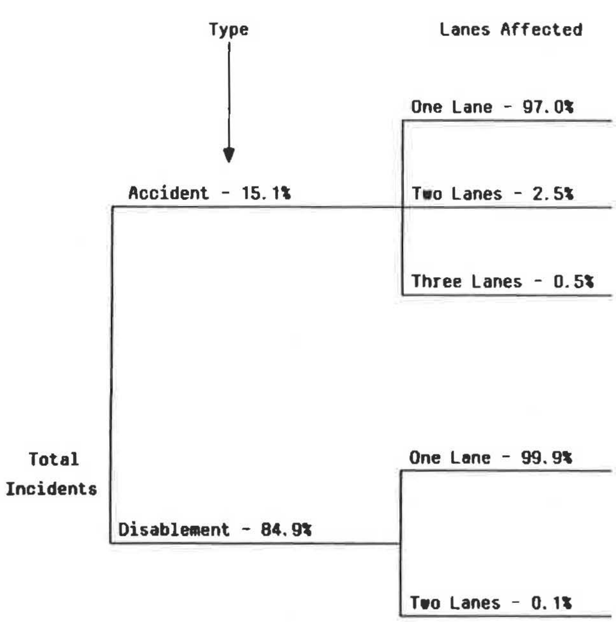

FIGURE 4 General incident tree (no shoulders).

Excess fuel consumption for nonrecurring congestion is calculated manually by assuming that the fuel consumption relationship previously expressed for recurring congestion also holds for nonrecurring congestion. Excess fuel consumption for nonrecurring congestion can thus be calculated for each of the freeway sections when delay due to incidents occurs.

The last step in the analysis program consists of calculating total user costs based on delay and excess fuel consumption. User costs due to time lost were calculated on the basis of a unit value of time derived by using the 1977 AASHTO Red Book (*9*). This publication quotes a 1977 value of time for 5 to 15 min of delay per trip (typical for an average urban freeway trip) as \$2.40/traveler hour for work trips. This value of time was expanded by using the Consumer Price Index to an October 1985 (*10*) value and an average vehicle occupancy of 1.25 was assumed, which yielded an average value of travel time of \$6.25/vehicle-hr. Other studies have calculated an even higher value of travel time (*11*). A value of \$1.00/gal was assumed for the cost of fuel.

TABLE 1 FRACTION OF FREEWAY SECTION CAPACITY AVAILABLE UNDER INCIDENT CONDITIONS

No. of Freeway Lanes in Each Direction	Shoulder Disablement	Shoulder Accident	Lane Blocked		
			One	Two	Three
2	0.95	0.81	0.35	0	0
3	0.99	0.83	0.49	0.17	0
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.25
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

TABLE 2 AVERAGE INCIDENT DURATION TIMES FOR FREEWAYS WITH ADEQUATE SHOULDERS

	Shoulder Disablement	Shoulder Accident	Disablement with Lane Blocked		Accident with Lane Blocked		
			One	Two	One	Two	Three
Detection	10	10	10	10	10	10	10
Response	10	10	10	10	10	10	10
Duration in lane after response	NA	NA	5	10	10	15	20
Total duration in lane	NA	NA	25	30	30	35	40
Duration on shoulder after response	10	20	15	15	20	25	30
Total	30	40	40	45	50	60	70

Note: All values are given in minutes. NA = not applicable.

TABLE 3 AVERAGE INCIDENT DURATION TIMES FOR FREEWAYS WITH NO SHOULDERS

	Disablement with Lane Blocked		Accident with Lane Blocked		
	One	Two	One	Two	Three
Detection	10	10	10	10	10
Response	10	10	10	10	10
Duration in lane after response	10	25	30	40	50
Total	30	45	50	60	70

Note: All values are given in minutes.

TABLE 4 URBAN FREEWAY CONGESTION STATISTICS

Item	1984	2005
Freeway miles	15,335	15,335
Vehicle miles of travel (millions)	276,645	410,987
Recurring congested vehicle miles of travel (millions)	31,486	98,280
Recurring delay (million vehicle hours)	485.0	2,048.6
Excess fuel consumption due to recurring delay (million gallons)	531.6	2,173.2
Delay due to incidents (million vehicle hours)	766.8	4,857.5
Excess fuel consumption due to incidents (million gallons)	845.9	5,143.9
Total delay (million vehicle hours)	1,251.8	6,906.1
Total excess fuel consumption (million gallons)	1,377.5	7,317.1
Total user costs ($ millions)	9,201.3	50,480.2

ANALYSIS RESULTS

As previously noted, the analysis program was applied to the HPMS database to obtain an estimate of national urban freeway congestion parameters. Table 4 shows the results of this analysis for both 1984 and 2005 (year 2005 AADT is an HPMS data item). These results are illustrative of the type of results one may expect when using the program for a specific freeway section or urban area. Those desiring further information on the results and conclusions of the study from which the methodology described is extracted should obtain a copy of the FHWA staff research study report *Quantification of Urban Freeway Congestion and Analysis of Remedial Measures* (*12*). The author may be contacted regarding the availability of this report.

SUMMARY AND FUTURE PLANS

This paper has described a computerized methodology developed for calculating the urban freeway congestion parameters of congested travel, recurring delay, nonrecurring delay, excess fuel consumption, and user costs. The methodology can be applied to single freeway sections or groups of freeway sections within an urban area. The methodology was used with a national database to quantify the urban freeway congestion problem.

The analysis program, as currently written, is tailored to the characteristics of the HPMS database. To permit its use by others, the program will be enhanced to allow direct user input. The user will be allowed to use default values for certain parameters, such as the value of travel time, or to substitute his own values. The revised program will run on an IBM-PC or compatible microcomputers and will be fully documented.

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