QUANTIFICATION OF URBAN FREEWAY CONGESTION AND ANALYSIS OF REMEDIAL MEASURES

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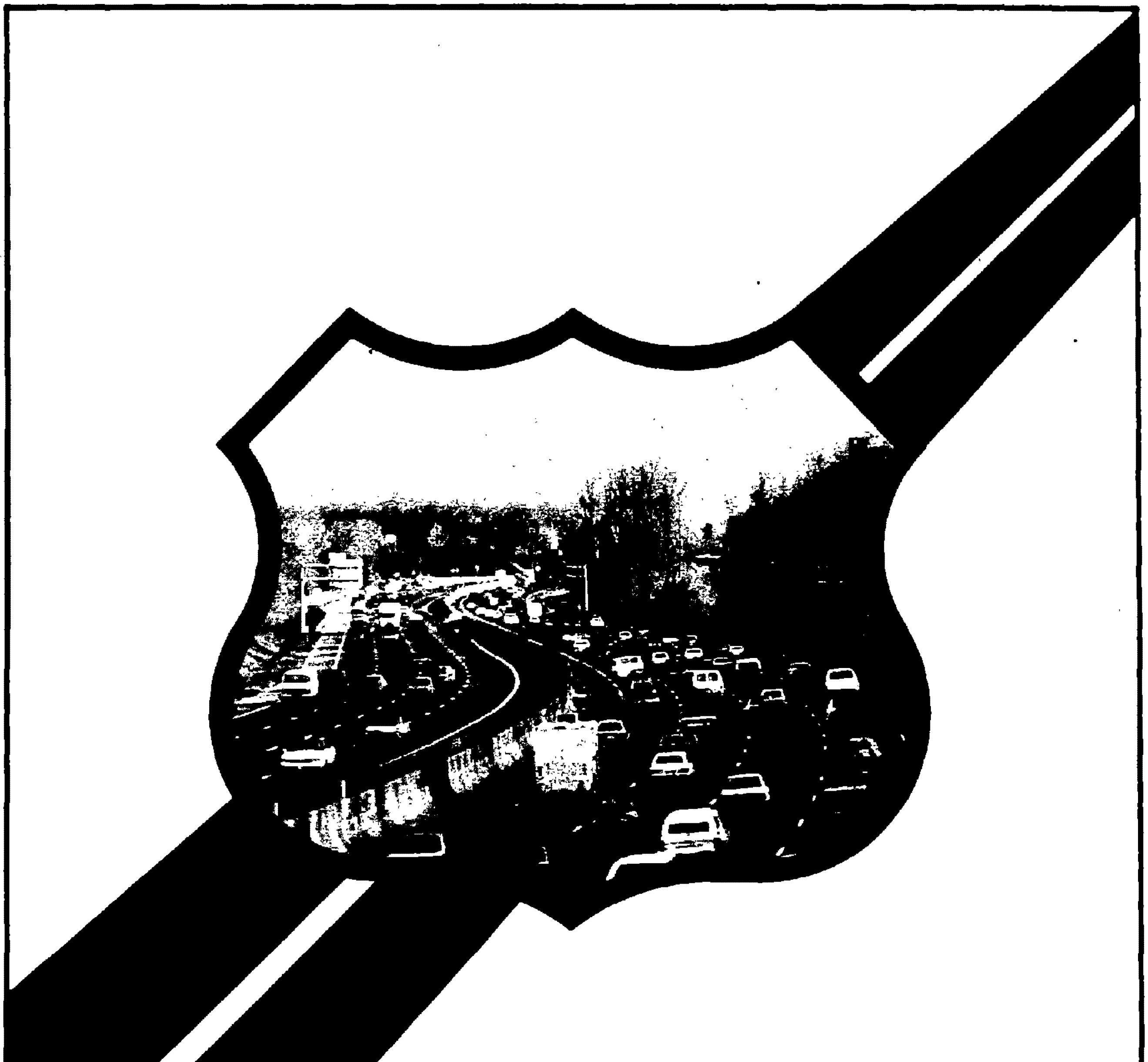

FOREWORD

This report is a result of the staff study, "Quantification of Urban Freeway Congestion and Analysis of Remedial Measures." The report will be of interest to traffic engineers, planners and managers in urban areas affected by the growing urban freeway congestion problem.

This research used the geometric and traffic data contained in FHWA's Highway Performance Monitoring System (HPMS) database to make estimates on a National basis of the impacts of urban freeway congestion for the years 1984 and 2005. The aggregate impact of several of the most common techniques for alleviating urban freeway congestion was also investigated.

The research reported herein is part of Nationally Coordinated Program (NCP) Program Area B.1, "Traffic Management Systems."

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NOTICE

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16. Abstract

This report presents an estimate of existing (1984) and future (2005) levels of congestion on the Nation's urban freeways based on data contained in FHWA's Highway Performance Monitoring System (HPMS) database. Estimates of congested travel, delay due to recurring congestion, delay due to non-recurring (incident) congestion, and wasted fuel are made on a national basis. Estimates of the aggregate impacts of several techniques for reducing freeway congestion, such as widening, surveillance and control systems, low-cost geometric improvements, and demand reduction strategies are also made.

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1. INTRODUCTION

Urban congestion is a serious and worsening National problem, one which is receiving increasing attention from transportation engineers, planners, and researchers as well as other local, State, and National officials. The Institute of Transportation Engineers (ITE) held a National conference in May of 1985 to specifically address the problem of urban congestion and plans to hold similar conferences in 1987. The Transportation Research Board's National Cooperative Highway Research Program (NCHRP) recently funded over $1,000,000 of research to address the urban congestion problem. Urban congestion stories appear frequently in the media, particularly in large urban areas.

Freeways form a very important part of the urban transportation network. In 1984, freeways comprised only 2.6 percent of the roadway mileage in urban areas, yet accounted for 29.8 percent of the total travel[1]. The impact of a congested freeway can be felt throughout an urban area. Motorists seeking to avoid the congested freeway may use parallel arterial routes or other freeways which in turn increases congestion on these facilities. Traffic waiting to enter the congested freeway may spill onto adjacent surface streets, further aggravating congestion.

Several types of solutions to the urban freeway congestion problem currently exist. Adding freeway capacity through widening remains a viable option in many areas, though funding constraints hinder its widespread implementation. More and more, local authorities are turning to other, less costly types of improvements to alleviate freeway congestion, such as surveillance and control systems, ramp metering, incident management, motorist information systems and low-cost geometric improvements. These types of improvements have been implemented with varying degrees of success throughout the country.

One of the problems with trying to view the problem of urban freeway congestion and its potential solutions from a National perspective is that no detailed quantification of either the size of the problem or its projected future growth has been available. These figures are needed before estimates of the effectiveness of the various improvement types listed above in addressing the problem can be made.

The purpose of this study was to quantify the National problem of urban freeway congestion in understandable terms for both existing and expected future traffic levels and to analyze the aggregate impacts of various methods of solving the problem.

2. DESCRIPTION OF THE DATABASE

The first step in attempting to quantify and analyze the National problem of urban freeway congestion was to select an appropriate source of data. The requirements for this database were that it should (1) be Nationally oriented and (2) contain either detailed congestion information or enough detailed information on roadway and traffic conditions for congestion data to be derived.

The database chosen for this study was the Highway Performance Monitoring System (HPMS) database maintained by the Federal Highway Administration (FHWA). The HPMS database consists of detailed geometric, traffic and other data for a representative sample of roadway sections throughout the Nation. This sample can be used to represent the total highway system through the use of appropriate expansion factors supplied by each State. The sample section data and expansion factor information are resubmitted annually. One of the reasons for using the HPMS database for this study was the high rate of sampling for freeway sections. Approximately 50 percent of the urban freeway mileage is sampled, which results in good statistical reliability for the data on a National or Statewide basis.

For the purpose of this study, a subset of the overall HPMS database containing only data for urban freeway sections was obtained. The most recent data available during the performance of this study contained 1984 information for 48 States and the District of Columbia. 1984 data from the remaining two States, New Mexico and Tennessee, were unavailable. Earlier data were obtained and updated to 1984 for these two States.

The HPMS data subset obtained contained data from two FHWA functional classifications, urban Interstate and urban other freeway and expressway. These two functional classifications contain all of the urban freeway sections sampled. The HPMS system also separates urban data into two groups, small urban (population less than 50,000 persons) and urbanized (population greater than 50,000 persons). After a preliminary review of the data was performed, it was decided to limit the freeway sections considered in this study to those in the urbanized group, since there was virtually no congestion on the small urban sections. The resulting data set contained 4,646 sections representing 9,349 miles of urban Interstate and 3,390 sections representing 5,986 miles of urban other freeway and expressway.

Table 1 lists the key data items obtained for each sample section in the database. This list is only a subset of the actual data contained in the HPMS system. Each unreduced data record in the HPMS system can contain approximately 70 individual data items. The items listed in Table 1 are those which were used directly during the course of this study.

Table 1. Key Data Items in HPMS Data Base

Identification Data

- o State code
- o County code
- o Urban area code
- o Section identification
- o Functional classification
- o Route number

Physical Characteristics Data

- o Section length/expansion factor
- o Number of lanes
- o Lane width
- o Shoulder type/width
- o Median type/width
- o Widening feasibility
- o Speed limit

Traffic Data

- o Annual average daily traffic (AADT)
- o Percent trucks
- o K-factor
- o Directional factor
- o Capacity
- o Future AADT

Accident Data

- o Number of fatal accidents/fatalities
- o Number of non-fatal injury accidents/injuries
- o Number of pedestrian fatalities
- o Number of pedestrian injuries

Each States' use of the accident reporting portion of the HPMS system is optional. A brief comparison of the accident data in the HPMS data subset and data available from the National Highway Traffic Safety Administration (NHTSA) indicated that few of the States report all of their accidents through the HPMS system. Several States do not use the HPMS accident reporting features at all. Due to the incompleteness of this portion of the database, it was determined that the HPMS data could not be used to quantify and analyze freeway delay due to non-recurring congestion. The alternative analysis method chosen for this task is described in Section 3.

As a note on the reliability of the database, the quality of the HPMS data set, and thus the accuracy of any analysis of the data, is only as good as the information supplied by each of the States. While the overall quality of the data is very good, some anomalies in the way some of the data are coded and reported by the various States were noted during the analysis. For instance, several States appear to use only one or a few different peak hour percentages (K-factors) for large groups of their freeway sections, rather than basing the values of these factors on more accurate count data. With the exception of coded capacity (which is discussed in Section 3), no attempt was made to change reported data which looked questionable. The number of sections containing these data anomalies was very small compared to the total number of sections (8,036) and it was not felt that the accuracy of the overall results of the study were jeopardized. However, some localized inaccuracies in the results may exist.

3. QUANTIFICATION OF EXISTING AND FUTURE URBAN FREEWAY CONGESTION

Methodology

In order to quantify the National problem of urban freeway congestion using the HPMS data, a methodology was required to convert the geometric and traffic information in the HPMS system into accurate and understandable measures of congestion. The size of the database (over 8,000 freeway sections) suggested a computerized analysis technique. A computer program written in FORTRAN IV for the IBM-PC microcomputer was developed to analyze the HPMS data. The program was written and structured to facilitate its reuse in future years if the analysis technique is favorably received. Figure 1 is a flowchart of the steps in the analysis program. Each of the major steps and how it was developed are described in the paragraphs below.

After initializing the totals for the various calculated parameters, reading each record and expanding the section length to the total represented mileage, the first major step of the program is to check the accuracy of the coded capacity of the section. This step was written into the program after one of the early validity checks performed on the HPMS data, a calculated peak hour volume/capacity (V/C) ratio, revealed some unexpected results. Many of the calculated V/C ratios were greater than 1.0. While theoretically not possible, a calculated V/C ratio of slightly greater than 1.0 is generally considered valid, representing the situation where demand exceeds capacity and level of service F (stop and go) traffic conditions prevail. However, several of the calculated V/C ratios were much greater than 1.0, a few greater than 1.5. This situation is clearly impossible. Review of the input data for these sections indicated that many of the capacities appeared to have been understated. Since section capacity would play a critical role in calculating delay and other congestion indices, it was decided that the apparently erroneous capacity values should be corrected.

Unlike other data, which would have been difficult to check or adjust without knowledge of the highway facilities in question, checking and adjusting the capacity of each section was a relatively straightforward process. In making their 1984 HPMS submissions, the States were required to use the methodology in the 1965 Highway Capacity Manual (HCM)[3] to estimate capacity. The methodology in the 1965 HCM calculates capacity as follows:

$$C = 2000\ NWT$$

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

Number of lanes, lane width and percentage of trucks are all HPMS data items. Lateral clearance effects can be approximated, since both right and left shoulder width are also HPMS data items. Thus a very close approximation of the actual section capacity can be calculated and compared to the capacity coded by the State. If the coded value was less than 90 percent of the calculated value, it was assumed that the coded value was incorrectly calculated and section capacity was changed to 90 percent of the calculated value.

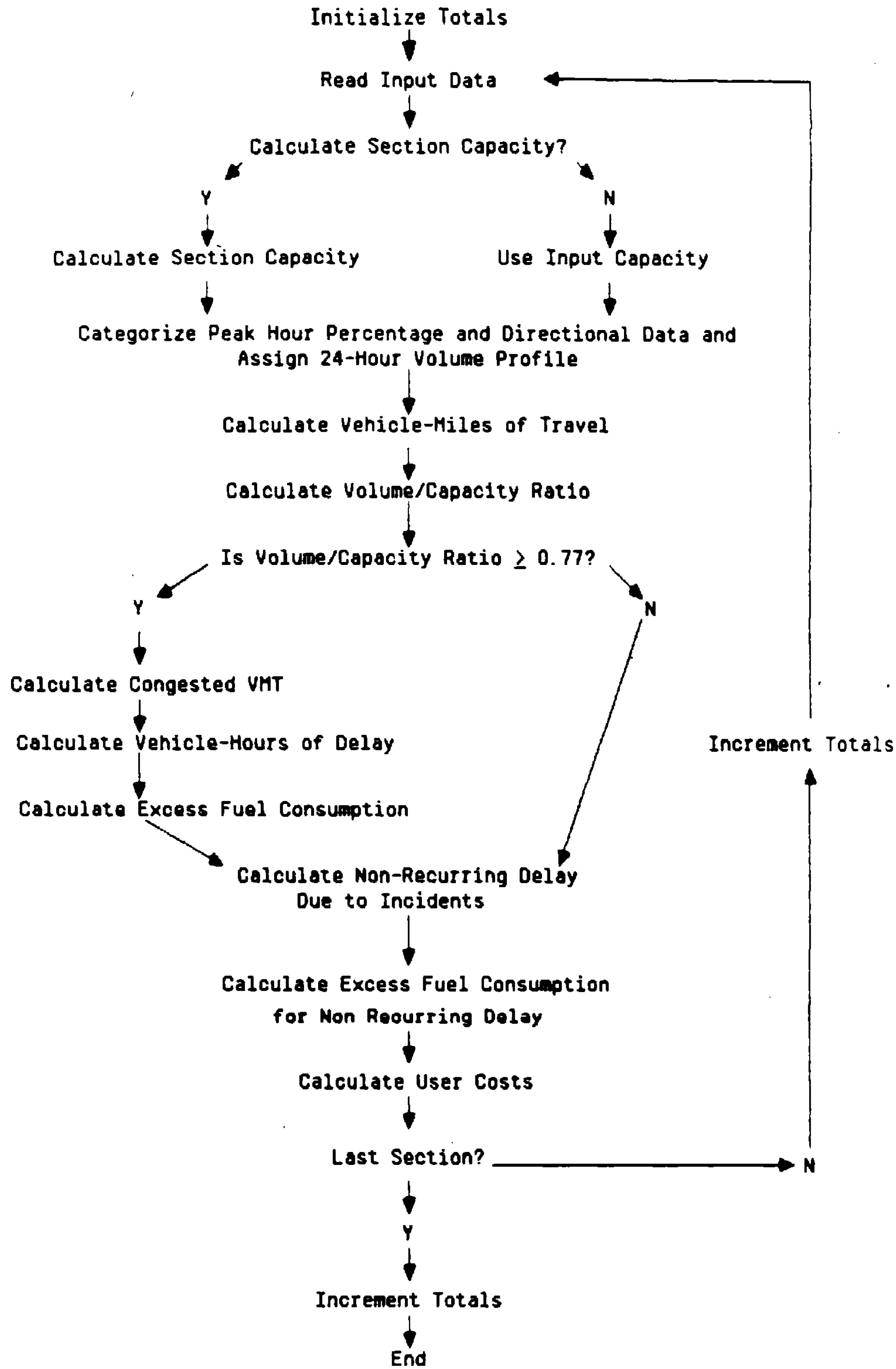

Figure 1. Steps in Analysis Program.

The next step in the analysis program is to assign a 24-hour volume profile to each freeway section. Because the HPMS data includes a traffic percentage and directional factor for the peak hour only, a method to deduce the traffic characteristics for times other than the peak hour was necessary. To accomplish this, 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 these counts, a total of 12 24-hour volume profiles (expressed in terms of percentage of annual average daily traffic (AADT)) were developed for a "typical" urban freeway for various peak hour traffic percentages and directional factors. For each HPMS freeway section, the coded data on peak hour traffic percentage and directional factor were used to select an appropriate 24-hour volume profile for that section. Thus, estimated hourly directional traffic volumes were available for each HPMS freeway section.

In the next step of the program, total annual vehicle-miles of travel were calculated for each HPMS data section. Since the HPMS data includes the annual average daily traffic volume for each section 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
365 = days per year

Before performing the calculations for annual congested vehicle miles of travel, it was necessary to select a point at which congested flow begins. For the purposes of this study, 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 to the same trip under low volume conditions. The numerical values selected to describe this point were taken from the 1985 Highway Capacity Manual (HCM)[4]. Table 3-1 of this reference gives density, average travel speed, volume/capacity (V/C) ratio, 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 miles per hour, V/C ratio 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 ratio 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 is in close agreement with values used in the Department of Transportation's reports to Congress on the status of the Nation's highways (congestion occurs where $V/C > 0.8$)[5] and the American Association of State Highway and Transportation Officials' (AASHTO) recommended design standard for urban freeways (design for $V/C < 0.8$)[4]. A V/C ratio was calculated for each HPMS freeway section for each hour of a typical day. If the V/C ratio was greater than or equal to 0.77, the flow on the section was considered to be congested and the travel occurring on the section during the hour was considered congested travel.

The formula for calculating total annual congested vehicle miles of travel is similar to the formula given above 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
AADT = annual average daily traffic
LENGTH = expanded section length
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 likely a slightly conservative estimate. For V/C ratios 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)[4]. As shown on the figure, for 70 mph design facilities, average travel speed varies between 30 and 54 mph for V/C ratios between 1.00 and 0.77. Finally, for V/C ratios greater than 1.0 (representing Level of Service F conditions) an average travel speed of 20 mph was assumed. Selection of this value was largely subjective, but it is in close agreement with other values given in the literature[6].

Total annual delay due to recurring congestion was 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 is 55 mph)
ACTUAL = actual section travel time per vehicle (less than ideal average speed)
PCT = percentage of daily traffic experiencing congested conditions
AADT = annual average daily traffic
260 = days per year when recurring congested conditions occur

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

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

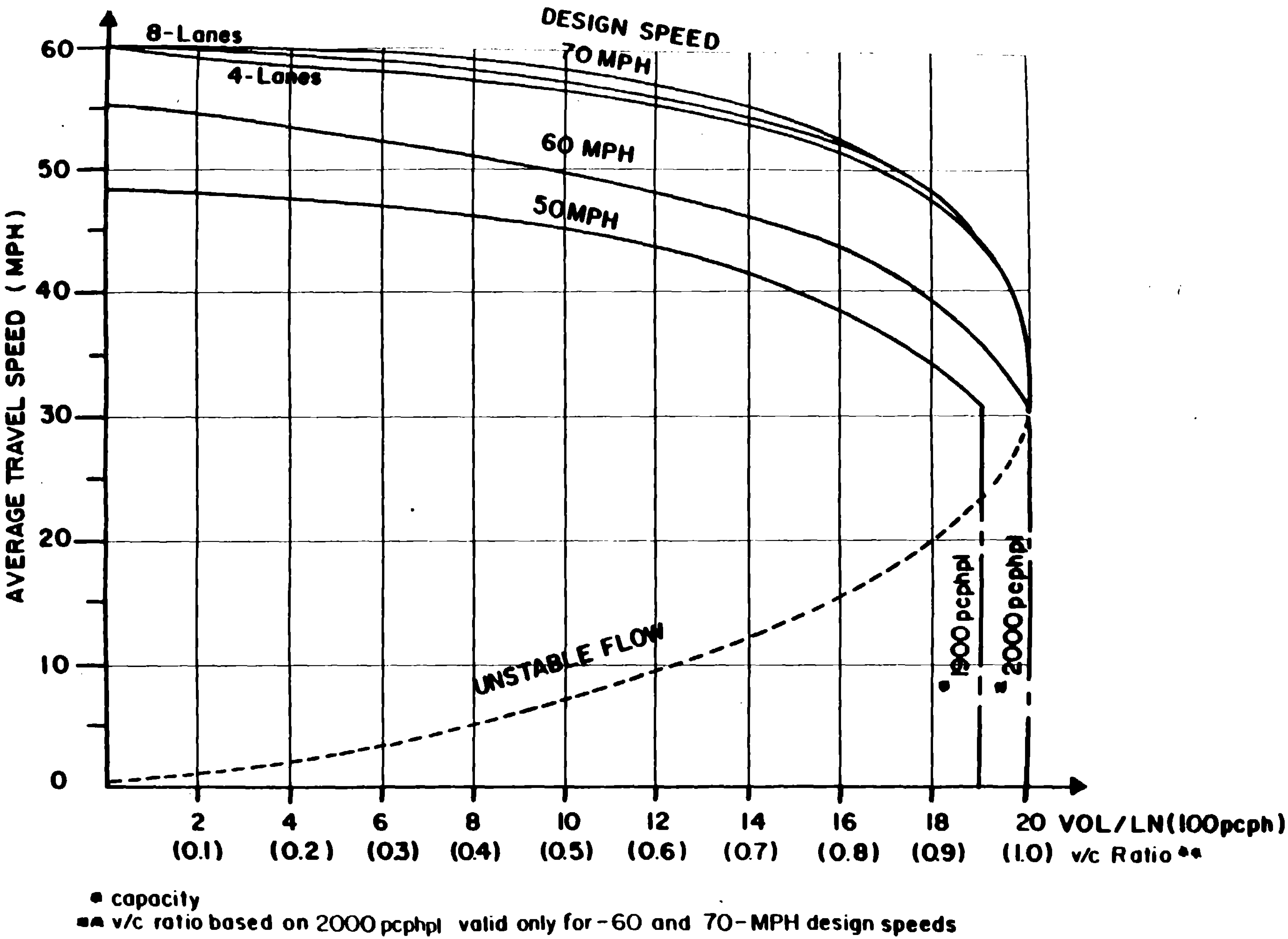

Figure 2. Speed-Flow Relationships Under Ideal Conditions. (Source: Reference 4)

Since it was not desired to perform fuel consumption research as part of this study, it was decided that a modified version of the fuel consumption data reported by Raus in 1981[7] would be used. In this study, fuel consumption values for average speeds between 1 and 35 miles per hour 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 this data to determine an appropriate linear relationship which could be extended to average speeds up to 55 mph. The resulting expression is as follows:

$$MPG = 8.8 + 0.25\ AVGSPD$$

where MPG = average fuel economy (miles per gallon)
AVGSPD = average travel speed (miles per hour)

Since 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 non-recurring congestion due to disabled vehicles and accidents. Since accident reporting in the HPMS system is incomplete and statistics for disabled vehicles are not included, an alternative method for making this estimation was used. This method was based on previous work done on low-cost freeway incident management techniques.[8] In this procedure, delay due to an incident can be estimated if information on freeway capacities and volumes and incident duration are known. The basic strategy for this study was to apply the incident delay procedure repetitively for each freeway section for each hour of a typical day to estimate the total delay due to incidents.

To estimate total delay due to incidents, an average set of incident frequencies for various incident types was necessary. This data was obtained from the previous study on low cost freeway incident management techniques. For this study, 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 for this study.

As noted above freeway capacity under normal (non-incident) conditions is an HPMS data item which is checked and adjusted by the analysis program if necessary. Typical directional traffic volumes for each hour of the day are also derived as noted above. 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 4, 6, and 8 lane freeways and are expressed in terms of vehicles per hour for typical capacity conditions (capacity = 1850 vehicles/ lane/hour).[8] For this study, it was more useful to express these values in terms of percentage of total capacity remaining during an incident. It was also necessary to

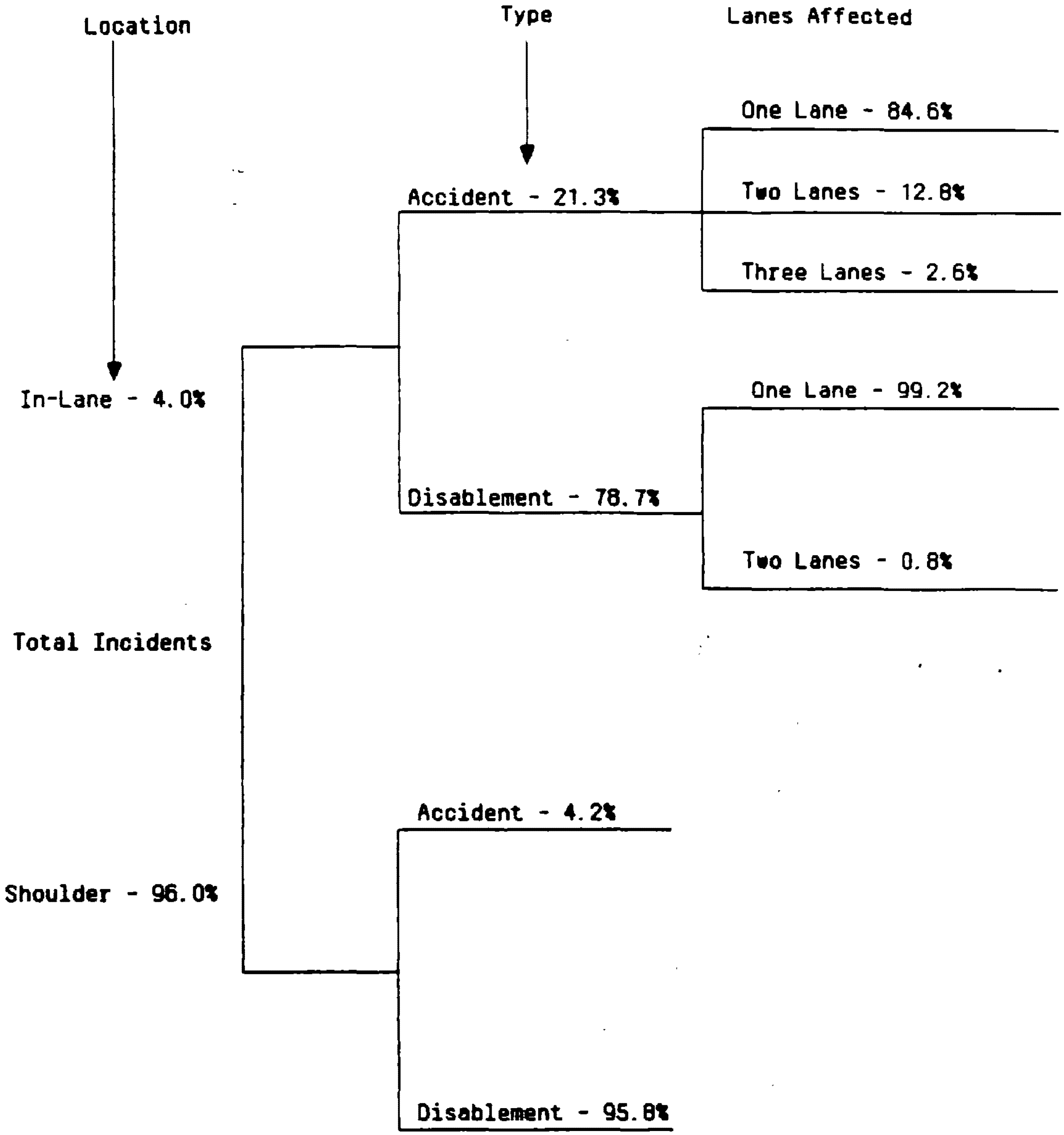

Figure 3. General Incident Tree (Adequate Shoulders)

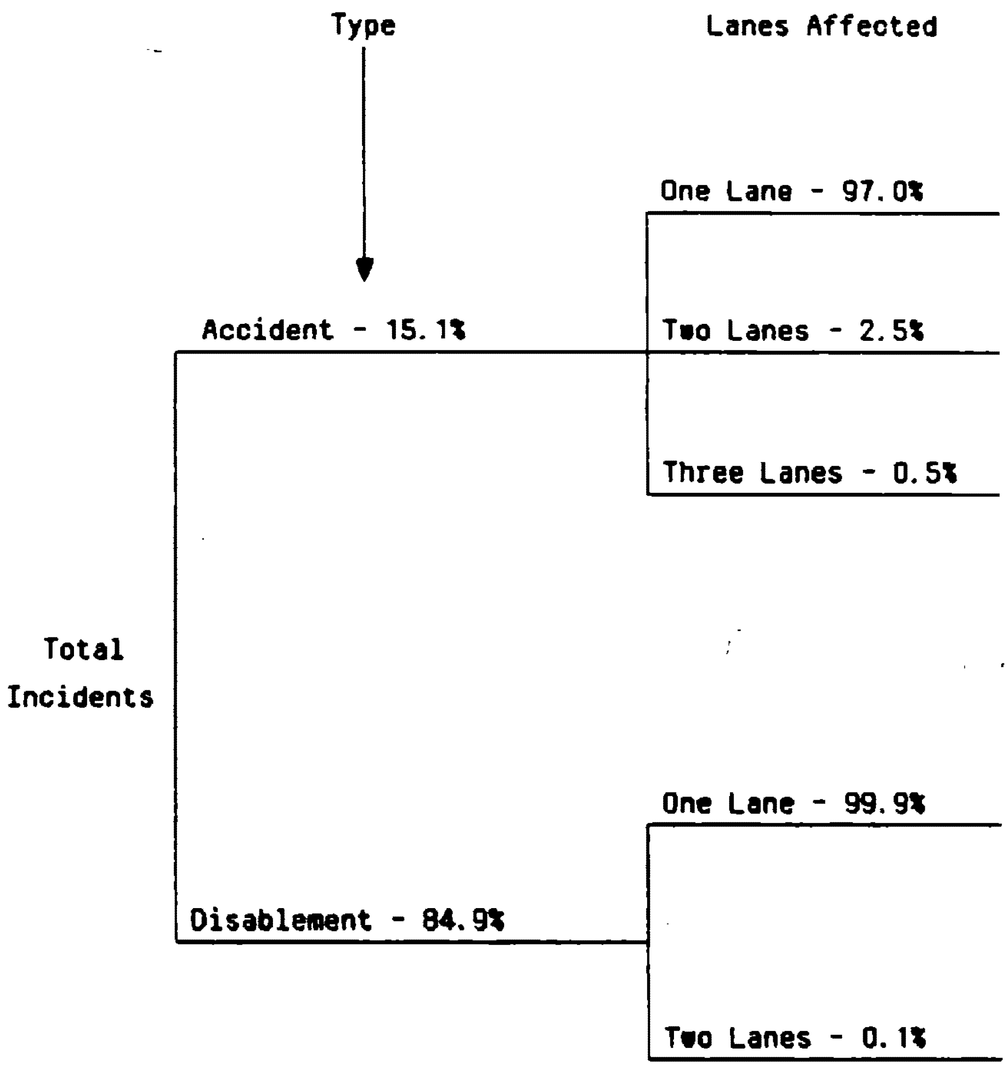

Figure 4. General Incident Tree (No Shoulders)

estimate values for shoulder disablements, two and three lane incidents, and freeway cross sections of as many as 16 lanes. The final values used in this study are shown in Table 2.

The average duration for incidents, including figures for both in-lane time and time spent on the shoulder, were estimated from several data sources based on actual detection, response and clearance times from operating urban freeways.[8 9 10] These values are shown in Tables 3 and 4. Since the values shown in the table are average 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 (1) calculation of the number of occurrences per year of a each incident type for each hour of the day using the incident trees shown in Figures 3 and 4, (2) calculation of the time until normal flow resumes following an incident using freeway capacity and traffic volume information and the values in Tables 2, 3 and 4, (3) calculation of delay caused by the presence of an incident for each 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.

Excess fuel consumption for non-recurring congestion is calculated by assuming that the fuel consumption relationship previously expressed for recurring congestion also holds for non-recurring congestion. Excess fuel consumption for non-recurring congestion is calculated for each of the freeway sections where delay due to incidents occurs.

In addition to analyzing existing (1984) traffic conditions, the analysis program also included the capability of analyzing year 2005 congestion levels based on volume projections supplied for each freeway section by the States. Since future traffic volume is the only future data item reported, the analysis of future congestion levels does not consider the effect of any improvements to existing facilities (other than the effect of planned new facilities reflected in the AADT projections) or any changes in the peaking characteristics of traffic. Thus, future estimates of congested travel, delay, excess fuel consumption and vehicle emissions are assumed to be overstated. However, they are very useful in further justifying the critical importance of making all feasible improvements to avoid the "worst case" 2005 scenario.

Analysis Results

Table 5 is a summary of the results of the analysis program for 1984 for the 15,335 miles of urban freeway contained in the data set. Review of this table indicates that urban freeway congestion results in over 1.2 billion vehicle-hours of delay and over 1.3 billion wasted gallons of fuel per year. Given an average value of time of $6.25 per vehicle-hour of delay (derivation of this value will be discussed in the next section) and an average cost of $1.00 per gallon of fuel, urban freeway congestion costs the motoring public over 9 billion dollars per year.

Table 2
Fraction of Freeway Section Capacity
Available Under Incident Conditions.

Number of Freeway Lanes In Each Direction	Shoulder Disablement	Shoulder Accident	1-Lane Blocked	2-Lanes Blocked	3-Lanes Blocked
2	.95	.81	.35	0	0
3	.99	.83	.49	.17	0
4	.99	.85	.58	.25	.13
5	.99	.87	.65	.40	.20
6	.99	.89	.71	.50	.25
7	.99	.91	.75	.57	.36
8	.99	.93	.78	.63	.41

Table 3
Average Incident Duration Times (Minutes)
For Freeways with Adequate Shoulders.

	Shoulder Disablement	Shoulder Accident	Disablement 1 Lane Blocked	Disablement 2 Lanes Blocked	Accident 1 Lane Blocked	Accident 2 Lanes Blocked	Accident 3 Lanes Blocked
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 Duration	30	40	40	45	50	60	70

Table 4. Average Incident Duration Times (Minutes) for Freeways With No Shoulders.

	Disablement 1 Lane Blocked	Disablement 2 Lanes Blocked	Accident 1 Lane Blocked	Accident 2 Lanes Blocked	Accident 3 Lanes Blocked
Detection	10	10	10	10	10
Response	10	10	10	10	10
Duration In-Lane After Response	10	25	30	40	50
Total Duration	30	45	50	60	70

Table 5
1984 Urban Freeway Congestion Statistics

Freeway Miles	15,335
Vehicle-Miles of Travel (Millions)	276,645
Recurring Congested Vehicle-Miles of Travel (Millions)	31,486
Recurring Delay (Million Vehicle-Hours)	485.0
Excess Fuel Consumption Due to Recurring Delay (Million Gallons)	531.6
Delay Due to Incidents (Million Vehicle-Hours)	766.8
Excess Fuel Consumption Due to Incidents (Million Gallons)	845.9
Total Delay (Million Vehicle-Hours)	1,251.8
Total Excess Fuel Consumption (Million Gallons)	1,377.5

Review of Table 5 also indicates that approximately 11.4 percent of all freeway travel in urban areas occurs under recurring congested conditions. Also, delay due to incidents accounts for approximately 61 percent of total urban freeway delay, a figure substantially higher than that normally quoted (50 percent).

Table 6 is a summary of the results of the analysis program for 2005. This table indicates that by 2005, urban freeway travel will increase to 276,645 million vehicle-miles, an increase of approximately 49 percent over the 1984 figure. As noted, the 2005 results are based on no improvements to the existing freeway system. Thus, they are illustrative of a worst case situation. Using this scenario, congested travel will increase by over 212 percent, recurring delay will increase by over 322 percent and delay due to incidents will increase by over 533 percent. Total excess fuel consumption due to urban freeway congestion will increase by over 431 percent. The disproportionate increases in delay as compared to fuel consumption indicate that urban freeway congestion will be much worse in 2005, both in magnitude and severity. Assuming similar monetary values for time and gasoline as expressed in 1984, the motoring public in 2005 will lose over $50 billion annually due to urban freeway congestion. Table 6 also indicates that by 2005, the percentage of total urban freeway travel occuring under recurring congested conditions will increase to approximately 23.9. Also, incident delay will comprise approximately 70 percent of all urban freeway delay.

Table 6
2005 Urban Freeway Congestion Statistics
(Based on No Improvements to Existing System)

Freeway Miles	15,335
Vehicle-Miles of Travel (Millions)	410,987
Recurring Congested Vehicle-Miles of Travel (Millions)	98,280
Recurring Delay (Million Vehicle-Hours)	2,048.6
Excess Fuel Consumption Due to Recurring Delay (Million Gallons)	2,173.2
Delay Due to Incidents (Million Vehicle-Hours)	4,857.5
Excess Fuel Consumption Due to Incidents (Million Gallons)	5,143.9
Total Delay (Million Vehicle-Hours)	6,906.1
Total Excess Fuel Consumption (Million Gallons)	7,317.1

4. ANALYSIS OF REMEDIAL MEASURES

As stated in the introduction to this report the goals of this study were two-fold. The first objective was to quantify the problem of urban freeway congestion. This has been accomplished by the analysis in the previous section. The second goal, to evaluate the potential effectiveness of several types of remedial measures in solving the problem, is the subject of this section.

There are many possible remedial measures to address a specific freeway congestion problem. These include geometric improvements, entrance ramp control, High Occupancy Vehicle (HOV) techniques, surveillance, incident management, diversion techniques, and control of traffic through work zones.[11] For this study, the remedial measures selected for analysis fell into three broad categories: widening, implementation of surveillance and control systems and low cost modifications to increase capacity (e.g., using the shoulder as a travel lane). These three categories of improvements were chosen because they are typically among the most effective in reducing urban freeway congestion and because they could be directly analyzed using data in the HPMS system. Each of these three improvement types and the strategy for analyzing its effectiveness are described in detail below.

Widening

This improvement consists of adding lanes to the congested freeway, including all necessary geometric and structural changes at ramps, interchanges, bridges, etc. This improvement can be easily analyzed using data in the HPMS system, since one of the coded data items relates to widening feasibility. In their HPMS data submittal, the States are asked to assess the widening feasibility of each sample section. This assessment is based strictly on the presence of physical obstructions, such as severe terrain, buildings, cemeteries and parkland. Other factors, such as current right-of-way width, State practices concerning widening, projected traffic and political concerns are not considered.[2] Analysis of freeway sections where widening is feasible is very straightforward. Capacity for the section is recalculated considering the increased number of lanes and revised congestion parameters (congested travel, delay, and excess fuel consumption) are calculated using the analysis program.

Surveillance and Control Systems

This improvement consists of installing a comprehensive surveillance and control system for the congested segments of the freeway. As a minimum, such a system would contain mainline and ramp surveillance through loop detectors, a traffic responsive ramp metering system, and an incident management program. The effects of such systems have been well documented in the literature. Effects of a comprehensive surveillance and control system generally include reduced delay for vehicles on the freeway due to smoother merging, increased delay on the ramps due to the ramp meters, and reduced delay due to incidents for all vehicles. Some systems have also been responsible for a substantial decrease in the number of accidents on the freeway, with some reported accident reductions as high as 58 percent.[12] For this study, it was decided to quantify the benefits of a freeway surveillance and control system as a 20 percent improvement in average travel time on congested segments of the freeway. This figure includes the effects of increased delay on the ramps and is based on figures quoted by Wagner in 1980.[12] This figure agrees with data reported for more recently installed systems. The potential accident benefits of a surveillance and control system are difficult to quantify on a general basis and were not considered in the analysis. However, a 10-minute average reduction in incident duration was assumed because of the incident management program. As with the widening improvement alternative, the effects of installing surveillance and control systems for congested freeway segments were easily analyzed. Average travel speed for each of the congested freeway segments was increased by 20 percent (not to exceed 55 mph) to simulate the implementation of a freeway surveillance and control system. Revised calculations for congested travel, delay, and excess fuel consumption were then performed by the analysis program.

Low Cost Modifications

This improvement consists of performing lower cost geometric modifications to a congested freeway in lieu of a full scale widening project. Such improvements typically include using one or both of the shoulders as travel lanes or reducing existing lane widths to provide an additional lane. Such projects are typically performed where physical widening is not possible or as a low cost temporary measure until a more extensive widening project can be funded. The benefits of projects of this type have been impressive. Capacity increases when low cost improvements are implemented have approached increases associated with physical widening projects. Accident rates have generally been reduced or remained constant, even though lane and shoulder widths have been reduced.[13]

Analysis of low cost modifications is slightly more involved than that for widening or surveillance and control projects. First, for each freeway section the feasibility of a low cost improvement is determined. It was decided that if a freeway was provided with paved shoulders, this improvement would be feasible if at least one additional lane could be provided in each direction while retaining at least 11 foot lanes and an 8 foot shoulder on one side of the roadway. For freeway sections where low cost improvements are feasible, the capacity of the section is then recalculated given the added lane(s) and reduced lane and shoulder widths. Congested travel, delay, and excess fuel consumption are then recalculated by the analysis program.

Costs of Remedial Measures

To permit an economic analysis of the various types of remedial measures, costs and benefits for the various remedial measures were calculated. Costs for each type of project were calculated using an assumed project scope. The unit cost for the various improvement types are given in Table 7 and are described in detail below.

For widening projects, it was assumed that one full lane would be added to the freeway in each direction, that the useful life for this new lane is 20 years, and that resurfacing of the new lane would be required after 10 years. The initial construction cost per directional mile of this type of improvement was calculated to be $2.5 million. This cost is based on the cost of recent similar projects of this type updated for inflation.[14] The resurfacing cost for one directional lane of freeway was estimated to be $150,000 and the annual maintenance cost for such a section was estimated to be $6,000. Again, these costs are based on recent similar projects of this type.[14]

Table 7
Estimated Project Costs

	TYPE OF IMPROVEMENT		
Item	Widening	Surveillance and Control	Low Cost Modification
Construction and Engineering	$5,000,000/mile	$1,000,000/mile	$1,300,000/mile
Maintenance	$ 12,000/year	$ 100,000/year	$ 12,000/year
Resurfacing (@ 10 years)	$ 300,000/mile	N/A	$ 300,000/mile
Useful Life	20 years	10 years	20 years

For surveillance and control projects, it was assumed that a system including loop detector surveillance, traffic responsive ramp metering and incident management components would be installed. Based on the costs of the most recent projects of this type installed in New York City and Washington, D.C., the approximate cost for such a system is currently $1 million per bi-directional mile of freeway.[15] The annual operating and maintenance costs for a surveillance and control system are widely quoted in the literature as being approximately 10 percent of the installation cost or about $100,000 per mile per year.[12 16] A 10-year life was assumed for a surveillance and control system.[12 16 17 18 19]

For low cost modification projects, it was assumed that a lane in each direction would be added within the existing paved right-of-way through restriping and minor geometric changes. However, it was also assumed that some of the pavement would require reconstruction to accommodate the loads from continuous heavy traffic. It was assumed for the average project that an 8-foot cross section of pavement would require reconstruction. These assumptions result in a cost of $650,000 per directional lane mile for this type of improvement[14] (perhaps "low cost" modification is a misnomer). It was further assumed that the additional travel lane would require resurfacing after 10 years. Resurfacing and annual maintenance costs would amount to $150,000 and $6,000 per lane mile per year respectively as given above for widening projects.

Benefits of Remedial Measures

Benefits calculated for each of the three improvement types fell into two categories -- benefits due to delay savings and benefits due to fuel savings. Benefits due to reduced air pollution, reduced accidents, reduced vehicle operating costs (other than fuel) and increased driving comfort are difficult to monetarily quantify and were not considered in the economic analysis.

Benefits due to time savings were calculated based on the number of vehicle hours of delay saved by each improvement alternative. A unit value of time was calculated using the 1977 AASHTO Red Book.[20] The Red Book quotes a 1977 value of time for 5-15 minute savings per trip as $2.40 per traveler hour for work trips. This value of time was expanded using the Consumer Price Index to an October 1985 value[21] and an average vehicle occupancy of 1.25 was assumed. This calculation yielded an average value of travel time of $6.25 per vehicle hour. Benefits due to fuel savings were calculated based on the number of gallons of fuel saved by each improvement alternative. A value of $1.00 per gallon was assumed for the cost of fuel.

Analysis Results

The costs and benefits for each of the improvement types described in the previous sections were amortized and converted to annual costs and benefits. For all projects, the investment interest rate was assumed to be 10 percent. Widening improvements and low cost modifications were considered for all congested freeway segments where feasible as described above. Surveillance and control projects were considered for all congested freeway sections. After "implementing" an improvement on a freeway section, the annual monetary benefits of the improvement were calculated and compared to the annual costs. An improvement type was considered cost effective for a particular freeway section if the expected annual benefits exceeded the estimated annual costs. Only cost effective improvements were included in the final analysis.

Table 8 is a summary of the results of the analysis program for each of the three improvement types for 1984 traffic conditions. Review of this table indicates that widespread implementation of low cost geometric improvements will result in the greatest total benefits for users of the urban freeway system (about $4.7 billion per year). Widespread implementation of widening and surveillance and control projects would result in approximately $3.1 and $3.0 billion in savings per year, respectively.

It was also desired to calculate the improvement in 1984 congestion levels attainable from a combination of the three improvement types. To perform this calculation, the analysis program was revised to allow surveillance and control projects to be implemented in addition to widening or low cost geometric improvement projects on the same freeway section, if cost effective. Widening or low cost geometric improvement projects were selected for each freeway section based on relative cost effectiveness. Thus, for the combined improvement analysis, a congested freeway section could have no improvements, a single type of improvement or a combination of improvements. The results of this analysis are shown in Table 9. As one would expect, combining improvement types results in annual monetary savings to freeway users which are greater than any of the three individual improvement types (about $6.5 billion per year). However, the savings/cost ratio is lower than that for surveillance and control or low cost geometric improvement projects.

The results of the analyses in Tables 8 and 9 contain some interesting implications. The first of these concerns the use of widening as a means of improving urban freeway congestion. The analysis results indicate that widening is cost effective for only about half the total freeway mileage for which surveillance and control projects or low cost geometric improvements would be cost effective. In terms of total monetary benefits, widening is about as effective as surveillance and control projects and considerably less effective than low cost geometric improvements. Widening has the lowest savings/cost ratio of the three improvement types analyzed. These results are likely due to the high capital cost of widening projects and the fact that, for many of the most congested freeways in the Nation, widening is not a feasible alternative.

A second implication of Tables 8 and 9 concerns the total impact of the three improvement alternatives analyzed on the total problem. Based on the figures in Table 5, the 1984 urban freeway congestion problem amounts to approximately $9.2 billion per year. The most effective of the improvement alternatives analyzed, low cost geometric improvements, eliminates only about half the problem. Implementing a combination of improvements eliminate about two-thirds of the problem. Thus, considering only these three improvement categories alone and in combination, a large portion of the urban freeway congestion problem is economically untreatable.

A final implication of Tables 8 and 9 concerns the level of funding required to achieve significant improvements in urban freeway congestion. For example, for the combined improvement scenario, under which 1984 urban freeway congestion is reduced by about 70 percent, an initial capital investment of over $10 billion would be required. This required investment level is much greater than the current annual level of capital outlay for urban freeway projects[1]. Also, this figure includes only improvements necessary to treat 1984 congestion

Table 8
Comparison of Effectiveness of
Improvement Types (1984)

	TYPE OF IMPROVEMENT		
	Widening	Surveillance and Control	Low-Cost Geometric Improvements
Improvable Miles	1,400	2,625	2,887
Recurring Delay Reduction (Million Vehicle-Hours)	145.0	137.0	239.3
Non-Recurring Delay Reduction (Million Vehicle-Hours)	298.7	286.0	412.6
Total Excess Fuel Reduction (Million Gallons)	407.1	308.6	607.7
Total Annual Savings	$3,180,000,000	$2,951,000,000	$4,682,000,000
Total Annual Costs	$ 941,000,000	$ 699,000,000	$ 641,000,000
Savings/Cost Ratio	3.4	4.2	7.3

Table 9
Effects of Combined Improvements (1984)

Improvable Miles	3,074
Recurring Delay Reduction (Million Vehicle-Hours)	336.2
Non-Recurring Delay Reduction (Million Vehicle-Hours)	565.6
Total Excess Fuel Reduction (Million Gallons)	843.4
Total Annual Savings	$6,479,000,000
Total Annual Costs	$1,821,000,000
Savings/Cost Ratio	3.6

levels. As noted in Section 3, urban freeway congestion is expected to grow quickly in the next 20 years and additional investment in improvements will be required.

The three improvement alternatives analyzed above all involve improving the "supply" of transportation facilities by increasing capacity or vehicle throughput characteristics. Another potential category of improvements involves reducing the "demand" on the facility. Typically, this involves establishing incentives for ridesharing or using mass transit. To analyze the potential impact of demand reduction, the analysis program was revised to simulate the effect of one driver of every five single occupant vehicles being removed from the peak period traffic stream by forming a carpool or using mass transit. In a typical urban area, this would result in approximately an 18 percent reduction in peak period traffic. The results of this analysis are shown in Table 10. Comparing the figures shown in Table 10 to those in Table 5 indicates that, under the reduced demand condition, the total reduction in 1984 urban freeway travel would be about 17 percent. Recurring congested travel would be reduced by 55 percent, recurring delay by 67 percent, and incident delay by 63 percent. The total annual cost of urban freeway congestion would be reduced from $9.2 billion to $3.3 billion (64 percent). Comparison of these figures to those in Tables 8 and 9 indicate that reducing demand by an average of 18 percent during the peak period would be more effective in eliminating urban freeway congestion than any of the three "supply" improvement alternatives analyzed and slightly less effective than the combined implementation of all three improvement alternatives. Thus, demand reduction strategies should be seriously considered when seeking solutions to urban freeway congestion problems.

Table 10
1984 Urban Freeway Congestion Statistics
with Demand Reduction

Freeway Miles	15,335
Vehicle-Miles of Travel (Millions)	230,018
Recurring Congested Vehicle Miles (Millions)	14,145
Recurring Delay (Million Vehicle-Hours)	161.6
Excess Fuel Consumption Due to Recurring Delay (Million Gallons)	186.6
Delay Due to Incidents (Million Vehicle-Hours)	284.6
Excess Fuel Consumption Due to Incidents (Million Gallons)	328.8
Total Delay (Million Vehicle-Hours)	446.2
Total Excess Fuel Consumption (Million Gallons)	515.4

5. SUMMARY AND CONCLUSIONS

Urban freeway congestion is a serious and worsening National problem. Freeway users currently waste more than $9 billion annually in time and excess fuel on congested urban freeways. Travel on urban freeways is expected to increase by nearly 50 percent by 2005 which will more than quintuple the amount of urban freeway delay unless significant improvements are made.

Widening, surveillance and control systems and low cost geometric improvements are examples of improvements which can be implemented on urban freeways to reduce congestion. Individual analysis of these improvements on a National scale indicates that widespread implementation of low cost geometric improvements would have the greatest impact on the urban freeway congestion problem for the lowest cost. A combined implementation of all three improvement types could cost effectively eliminate over two-thirds of the current urban freeway congestion problem, but only at a level of investment much higher than current funding levels. Demand reduction strategies, such as HOV projects, also have potential for significantly reducing the urban freeway congestion problem.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. **Highway Design and Operation for Safety**
   Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. **Traffic Control and Management**
   Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. **Highway Operations**
   This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. **Pavement Design, Construction, and Management**
   Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. **Structural Design and Hydraulics**
   Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. **RD&T Management and Coordination**
   Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.