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CALIFORNIA PATH PROGRAM  
INSTITUTE OF TRANSPORTATION STUDIES  
UNIVERSITY OF CALIFORNIA, BERKELEY

# **An Investigation of the Costs of Roadway Traffic Congestion: A Preparatory Step for IVHS Benefits' Evaluation**

**Mark A. Miller**  
**Kayin Li**

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May 1994

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**AN INVESTIGATION OF THE COSTS OF ROADWAY TRAFFIC CONGESTION**  
**A PREPARATORY STEP FOR IVHS BENEFITS' EVALUATION**

by

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## ABSTRACT

Intelligent Vehicle Highway Systems are currently under widespread investigation as a potentially viable means of addressing several of the current significant problems that the nation's surface transportation system experiences in the areas of congestion, safety, and air quality and energy use. A firm quantitative foundation of the baseline estimates of the state of these transportation-related problems is required prior to evaluating the benefits due to advanced transportation technologies.

The costs of traffic congestion under current road conditions was investigated to develop a quantitative understanding of such costs to provide the foundation for which future estimates of benefits due to advanced transportation technologies may be made. Initially, roadway traffic congestion were discussed in terms of its definition, its impacts, and means of measuring it. Alternative methods of quantifying the costs of traffic congestion were investigated based on research from the following four sources: Federal Highway Administration, Texas Transportation Institute, Southern California Association of Governments, and Caltrans. Summaries and reviews of each methodological approach as well as the extent of quantification for each study were documented. Moreover, conflicts among the congestion estimates were explained to facilitate a valid comparison among the studies. Travel time delay was the dominant contributing component to total congestion costs in all studies. In particular, recurring delay was the only impact of congestion common to all four studies, and non-recurring delay was common to all but the Southern California Association of Governments' study. Subsequent to comparing the delay estimates, their dollar value was also estimated.

The following recommendations for future research in this area were made: (1) development of a more unified approach for congestion measurement to improve estimation, (2) development of techniques to quantify the impacts of congestion that until now have only been considered qualitatively, and (3) development of a methodology to quantify non-recurring congestion.

Keywords: Intelligent Vehicle Highway Systems, benefits, quantifying, congestion, costs, delay

## EXECUTIVE SUMMARY

Applications of advanced transportation technologies with particular emphasis placed on Intelligent Vehicle Highway Systems (IVHS) are currently under widespread investigation as a potentially viable means of addressing several of the current significant problems that the nation's surface transportation system experiences. These problems may be grouped into the following three major areas: (1) congestion and constraints on mobility, (2) reductions in safety, and (3) energy inefficiency and degradations in environmental quality.

There are substantial federal and state research and development efforts to find solutions to these surface transportation problems. Part of this ongoing work is benefits' evaluation. In the evaluation of IVHS benefits, the investigation typically has a **before-and-after** comparative analysis framework. A baseline scenario or set of conditions (before state) is defined by the absence of any IVHS technology under study. The baseline scenario should contain as complete and accurate assessment of the problem, e.g. congestion or traffic-related accidents, as possible to better understand the benefits attributable to the specific IVHS technology under investigation, as well as to produce reliable and valid results. It would thus be valuable to examine the initial steps in the benefits' evaluation process which characterize the nature of the problem, e.g. congestion, from the standpoint of its definition, component causes and impacts, methods of measurement, and costs under current road conditions. Moreover, conflicts among alternative methods of quantifying congestion should also be resolved. After this examination a more comprehensive evaluation of IVHS benefits will be possible.

Numerous definitions of roadway traffic congestion exist based on different factors, such as the causes of congestion or the consequences of experiencing congestion. Moreover, numerous groups exist interested in congestion, such as governmental organizations, professionals including engineers, planners, lawyers, politicians, or administrators, the business community, the media, and the general traveling public. With such an array of interested parties a universally accepted definition of congestion would be difficult to derive. There is, however, consistency among alternative definitions and considering them provides a context within which congestion measures and congestion costs may be examined.

Roadway traffic congestion has the following impacts affecting individuals, businesses, as well as causing system-wide effects: delay and unreliability in travel time, reduction in levels of comfort and convenience, automobile insurance premium increases, health impairments, constraints on business growth, loss of efficiency in the overall transportation system, and environmental damage.

The following numerous congestion measures have been suggested or are in use to quantify roadway traffic congestion: average travel speed, traffic density, maximum service flow, volume-to-capacity ratio, average daily traffic, daily vehicle miles of travel, travel time, travel delay, throughput.

Several alternative methods of quantifying the costs of traffic congestion were investigated consisting of work by the Federal Highway Administration, the Texas Transportation Institute, the Southern California Association of Governments, and Caltrans. The Federal Highway Administration research derived the delay caused by vehicles **traveling**

under less than optimal free-flow conditions under both recurring and non-recurring congestion, and wasted fuel associated with such delay. The Texas Transportation Institute study similarly derived travel delay under both recurring and non-recurring congestion and wasted fuel, as well as increased insurance premiums. The Southern California Association of Governments research derived travel delay under recurring congestion, and numerous vehicle operating costs incurred due to congestion resulting from use of excess fuel and oil, wear and tear on tires, additional maintenance, and depreciation. Caltrans estimated recurring congestion-induced delay. Each of these four sources of information on the costs of traffic congestion was also reviewed with respect to underlying assumptions, available data sources, and specific analytical techniques to pinpoint strengths and weaknesses.

Travel time delay was the dominant congestion component in each of the four studies and delay for recurring congestion was the only component common to all four studies. Other congestion impacts were not quantified because of difficulty in some phase of the quantification process, for example, developing a methodological approach or collecting data.

Numerous differences exist among the studies that resulted in conflicts among estimates of congestion costs. These differences were examined and as many conflicts as possible were accounted for to facilitate a valid comparison of congestion costs across studies. Emphasis was placed on the four most heavily congested urban areas of California, namely, Los Angeles, San Francisco, San Diego, and Sacramento. A comparative analysis was performed relative to (1) daily recurring delay across all four studies for the Los Angeles region for freeways, and (2) daily recurring and non-recurring delay for all except the Southern California Association of Governments study for all four regions.

Caltrans recurring delay statistics are substantially less than for the other studies mainly because (1) Caltrans delay estimates are based on traffic during the morning and afternoon peak periods whereas the other studies are based on traffic throughout the day, and (2) Caltrans uses thirty-five miles per hour as its threshold of congestion, whereas the other research efforts use fifty-five miles per hour. The differences between the Federal Highway Administration and Texas Transportation Institute studies are principally due to (1) differences in the definition of the geographic region under consideration, either in terms of area or total number of center-line freeway miles, and (2) the use of only two values (peak and off-peak time periods) for average daily speeds (Texas Transportation Institute) versus average speed values for all hours throughout the day experiencing congestion (Federal Highway Administration).

Differences also exist in the non-recurring delay estimates. Caltrans assumes an equal split in total delay between recurring and non-recurring causes. The ratio of non-recurring to recurring delay for a given metropolitan area used in the Texas Transportation Institute study are based on the Federal Highway Administration study's **methodology**, and so the ratio is the same for these two studies. The Southern California Association of Governments study does not include non-recurring delay estimates.

Daily delay estimates for freeway travel were converted into user cost estimates in units of dollars to allow for a better appreciation of the **magnitude** and seriousness of the congestion problem. Values for vehicle occupancy, the dollar value of time, and the number of days per year when congested conditions occur were required to derive such cost

estimates. The relationships among the delay estimates across studies remain unchanged since each estimate was increased by the same factor. Annual user cost estimates in terms of 1993 dollars were found to be as follows: For recurring delay in the San Francisco region, user cost estimates ranged from approximately 196 million (Caltrans) to 975 million (Federal Highway Administration) and for non-recurring delay the range in cost estimates was from 196 million (Caltrans) to 1,279 million (Federal Highway Administration). For recurring delay in the San Diego area, user cost estimates ranged from approximately 43 million (Caltrans) to 131 million (Texas Transportation Institute) and for non-recurring delay the range was from 43 million (Caltrans) to 79 million (Texas Transportation Institute). In the Sacramento region, user cost estimates for recurring delay ranged from approximately 5 million (Caltrans) to 56 million (Federal Highway Administration) and for non-recurring delay, from 5 million (Caltrans) to 33 million (Federal Highway Administration). In the Los Angeles region, user cost estimates for recurring delay ranged from approximately 293 million (Caltrans) to 1,224 million (Texas Transportation Institute) and for non-recurring delay, from 293 million (Caltrans) to 1,469 million (Texas Transportation Institute).

The following recommendations for future research in this area were made: (1) development of a more unified approach for congestion measurement to improve estimation, (2) development of techniques to quantify the impacts of congestion that until now have only been considered qualitatively, and (3) development of a methodology to quantify non-recurring congestion.



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## 1. INTRODUCTION

Applications of advanced transportation technologies with particular emphasis placed on Intelligent Vehicle Highway Systems (IVHS) are currently under widespread investigation as a potentially viable means of addressing several of the current significant problems that the nation's surface transportation system experiences. These problems may be grouped into the following three major areas: (1) congestion and constraints on mobility, (2) reductions in safety, and (3) energy inefficiency and degradations in environmental quality. These problems will only worsen without intervention and threaten to continue to erode the transportation system's effectiveness at performing its function of safely and efficiently moving people and goods from origin to destination. Associated with solving these problems, or at least moderating their negative impacts, is also the potential for improving economic productivity. Nearly all economic activity uses transportation directly or indirectly, and improving the efficiency of the transportation system would likely boost economic productivity resulting from safety improvements, reduced traffic congestion delays, and efficient routing of vehicles.

Complete recognition of these problems and a substantial level of commitment toward finding solutions exist at various individual state levels as well as at the national level as exhibited in passage of the Inter-modal Surface Transportation Efficiency Act (ISTEA) of 1991 and Congressional authorization of \$660 million in funding for the national IVHS program for a period of six years. The national IVHS program includes a range of initiatives in the areas of research and development, system architecture development, operational tests, institutional/policy projects, and deployment projects (U.S. Department of Transportation, 1993).

Within the research and development domain is the area of benefits' evaluation. **In the** evaluation of IVHS benefits, the investigation that is performed typically has a before-and-after comparative analysis framework incorporating one or more of the following tools: (1) analytical techniques, (2) simulation modeling, (3) empirical data. A baseline scenario or set of conditions is defined by the absence of the IVHS component technology under study. The baseline scenario should contain as complete and accurate assessment of the problem,

e . g . congestion or traffic-related accidents, as possible to better understand the benefits attributable to the specific IVHS technology under investigation, as well as to produce reliable and valid results. It would thus be valuable to examine the initial steps in the benefits' evaluation process which characterize the nature of the problem, e.g. congestion, from the standpoint of its definition, component causes and impacts, methods of measurement, and costs under current road conditions. After this examination, a more comprehensive evaluation of IVHS benefits will be possible in future research.

### **1.1 Study Objectives**

This report focuses on traffic congestion under current road conditions with the objective of developing a quantitative understanding of their costs. This work will provide a foundation upon which to build later estimates of the benefits that could be attributable to the use of IVHS technologies.

### **1.2 Organization Of The Report**

This report is organized into four sections. Section 1 is the introductory section, providing the background and primary objectives for this research. Section 2 provides an overview of traffic congestion, including its definition, causes, impacts, and measurement. Section 3 summarizes (1) the principal sources of research in the areas of quantifying the costs of congestion and reviews this past work relative to the usage of data, methodological approaches used in the analysis, and assumptions, as well as (2) the California State Department of Transportation's (Caltrans') methods for quantifying congestion at the individual district level for those areas of the state experiencing the heaviest congestion. Section 4 consists of recommendations for future work in addition to conclusions and a summary.

## 2. ROADWAY TRAFFIC CONGESTION

In order to improve understanding of the costs of roadway traffic congestion and the attempts to quantify these costs, a brief overview of the basics of congestion-definition, effects, and measures is provided.

### 2.1 Defining Traffic Congestion

What is traffic congestion? To the general roadway traveler, congestion may be described by any of the following anecdotal “war” stories:

- The streets are clogged everywhere
- Second gear is the best I can do
- It took me forever to get home
- I was late to work three days this week
- It wasn't this bad a few years ago
- Now it's bad even on the weekends
- I missed an appointment and lost some business
- I am completely stressed out by the time I get to work
- Why don't they just expand the freeway?

While neither technical nor precise, they each contain grains of truth from which more precise definitions of congestion may be distilled for analytical purposes. The following list provides a sample of technical definitions for congestion appearing in the literature:

- a condition that arises out of the conjunction of two factors. The first is that every process [service] has a finite capacity. The second is that every process has a stochastic character: there is some degree of randomness in both the demands placed on a process and the ability of the process to service those demands. Congestion occurs when the average processing time per unit increases because of demand for services. (Manheim, 1984).
- a condition that arises because more people wish to travel at a given time than the transportation system can accommodate: a simple case of demand exceeding supply. (The Institution of Civil Engineers, 1989).
- any condition in which demand for a facility exceeds free-flow capacity at the maximum design speed. (Altshuler, 1981).
- a condition in which the number of vehicles attempting to use a roadway at any given



time exceeds the ability of the roadway to carry the load at generally acceptable service levels. (Rothenberg , 1985).

- an imbalance between traffic flow and capacity that causes increased travel time, cost and modification of behavior. (Pisarski, 1990).
- a condition which generally can be equated to long travel times and to delays in movement (Dickey, 1983).
- that condition represented by the additional daily travel time arising from reduced speed caused by traffic surges. (U.S. General Accounting Office, 1989).

These definitions and others refer to various factors related to congestion. Some are expressed in terms of the immediate causes of congestion (first four definitions listed above as well as last of the listed traveler perceptions), while others depict the results or consequences of experiencing congestion (last three definitions above and other traveler perceptions). Ongoing research in the area of quantifying congestion has proposed the following definition based on the effects of congestion:

Congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions. Moreover, the amount of congestion that is acceptable varies by type of transportation facility, geographic location and time of day. (Texas Transportation Institute, 1992).

Numerous groups exist with an interest in congestion, particularly in measuring congestion. Such groups include (1) governmental organizations (Departments of Transportation, Metropolitan Planning Organizations, Councils of Governments, and Transit Agencies), (2) professionals in engineering, planning, and related fields (transportation engineers and planners, land use planners, academic researchers), (3) other professionals (administrators, lawyers, politicians), (4) the business community, (5) the media, and (6) the general traveling public. With a vast array of interested parties, it would be difficult, were it the objective of this paper, to derive a single definition of congestion that is universally accepted. There is, however, a consistency among these alternative definitions and considering them provides a context within which congestion measures and the costs of congestion may be examined.

Roadway traffic congestion may be further partitioned into two types, recurring and non-

recurring. Recurring congestion is characterized by the repetitive nature of the traffic occurring during predictable times of the day when traffic volumes exceed the design capacities of the roadways and when the geometric design of the roadway does not allow a normal traffic flow. Such congestion occurs during the morning and afternoon peak travel periods common in urbanized areas. The problem of recurring congestion is exacerbated by random events, such as accidents, vehicle disablements, unexpected weather conditions, roadway construction or maintenance activities or other special events. These unexpected events produce non-recurring traffic congestion.

## **2.2 Impacts Of Congestion**

Roadway traffic congestion has numerous impacts that affect individuals and businesses, as well as cause system-wide effects.

### **2.2.1 Personal Impacts Of Congestion**

Delay and unreliability in travel time: Congestion causes delays and additional time must frequently be allowed for the completion of trips, since the delays are not predictable; even recurring congestion is not a completely deterministic process. Inefficiency in vehicle

operations: Congestion causes increases in (1) vehicle energy (gasoline or diesel fuel) consumption, (2) wear and tear on the vehicle's tires as well as on internal engine components, and (3) general added vehicle depreciation.

Reduction in levels of comfort and convenience: Overcrowding results in the loss of the general amenities of comfort and convenience while traveling in congested conditions.

Reduced safety: Even though accidents themselves are a cause of non-recurring congestion, both recurring and non-recurring congestion can lead to additional or secondary accidents resulting from drivers being required to pay much closer attention to congested traffic conditions or the rubber-necking effect from on-lookers driving in the opposite travel direction.

Automobile insurance premium increases: Congestion-induced accidents, in particular, in

urban areas, correlate with higher insurance premiums for motorists operating vehicles in these areas. Insurance premiums, however, are not only influenced by accident rates, since such premiums are also affected by crime rates within each urban area (Lomax, Bullard, and Hanks, 1988).

**Health impairment:** Congestion can lead to health-related problems as a result of regular and frequent (daily) exposure to sustained levels of stress due to driving under stop-and-go conditions requiring additional concentration and focus on driving defensively. Health-related effects such as the exacerbation of asthma or other upper respiratory conditions can also follow from congestion-induced increases in vehicle emissions (Assembly Office of Research, 1989). There are obvious health impacts of accidents, such as fatalities and injuries which are not caused by the resulting congestion. Quantifying such direct costs of accidents is not part of this report.

### **2.2.2 Business Impacts Of Congestion**

The congestion-related impacts described above can induce additional impacts on businesses generally in the area of constrained economic growth.

**Constraints on economic growth:** Congestion can result in the loss of business productivity and growth due to (1) lost output and deliveries and missed appointments, (2) increases in inventory holdings to safeguard against potential future delays, (3) reduced efficiency of commercial vehicle fleets resulting in less than optimal vehicle use, (4) time lost from employees (i) arriving late to work resulting in the need for additional hires, over-time pay, or managing absenteeism or (ii) taking sick leave due to congestion-induced health impacts, (5) less than optimal use of buildings, facilities, or property, and (6) reduced desirability of area for employees to live there, making it more difficult to attract good employees. This waste in resources can translate into economic growth restrictions.

### **2.2.3 Systemwide Effects Of Congestion**

**Loss of efficiency:** Congestion reduces the output of a transportation system, i.e. its

throughput, leaving it less able to manage the increased traffic volumes. As congestion increases, output decreases.

Environmental damage: Congested travel conditions result in worsening environmental problems such as air pollution, noise and visual impairments.

Restrictions on regional economic growth: The negative effects of congestion on individual businesses can have region-wide economic impacts.

## **2.3 Measuring Congestion**

Numerous measures have been suggested or are in use to quantify roadway traffic congestion. While none of these measures is universally accepted, alternative measures are valuable nonetheless since they reflect various facets of the problem. The following subsections briefly summarize major congestion measures appearing in the literature or are in use. Primary information sources are (Texas Transportation Institute, 1992) and (U. S . General Accounting Office, 1989).

### **2.3.1 Congestion Measurement States**

The scope of congestion measurement is based on several factors. A detailed discussion of these factors may be found in (Texas Transportation Institute et al 1992).

Spatial Scope: Spatial scope consists of identifying (1) the degree of geographic dispersion for the area under investigation, e.g. street intersection, freeway interchange, whole route, corridor, region, state, nation, (2) where and what type of area is under investigation, e.g. central business district (CBD) core area, CBD fringe area, central city, suburbs.

Temporal Scope: An important aspect of congestion to consider is the time at which it occurs. Examples of alternative times considered are (1) morning peak (peak 60 minutes, multiple hour period), (2) afternoon peak (peak 60 minutes, multiple hour period), (3) off-peak period, (4) daily, (5) weekday average, (6) peak month, (7) weekend, (8) annual average, and (9) occurrence of special events, e.g. football games or parades.

Roadway Facility Type: Another significant parameter is the type of facility under

investigation. Differences inherent in facility type determine differences in congestion measurement techniques used. Alternative roadway types include (1) freeways, (2) expressways, (3) principal arterials, (4) minor arterials, (5) collector roads, and (6) local streets.

Transportation Mode: Congestion is experienced for all modes of transportation. The impacts of congestion on commercial and multi-occupant vehicles, either buses, carpools, or vanpools, are as serious as the impacts on single-occupant vehicles.

General Framework: The planning, engineering or general analytical context within which congestion is measured is another dimension of the scope of congestion measurement. Congestion measures may be used to investigate requirements for changes as evidenced by existing conditions of travel demand and transportation facility supply. Examples of the framework within which congestion measurement is applied include: (1) existing conditions, (2) existing demand/modified supply, (3) future demand/existing supply, and (4) future year conditions.

### **2.3.2 Highway Capacity Manual Measures**

The Highway Capacity Manual (HCM) (Transportation Research Board, 1985) serves as a standard resource document for traffic engineering studies by most state and local agencies as well as a general research tool. The congestion measures described below focus on freeway segments. A range of operating conditions, or levels of service (LOS) has been developed to describe different traffic flow conditions that can exist on a given facility. The HCM describes six LOS using an ordinal scale from "A" to "F", similar to school grades with LOS A representing the best operating conditions consisting of free-flowing traffic and LOS F the worst condition, with unstable or breakdown traffic flow conditions. Each LOS describes traffic operating conditions in terms of speed, travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety. The following interrelated measures are used to quantify LOS (Transportation Research Board, 1985).

Average Travel Speed: Average travel speed is based on the travel time observed over a known length of freeway, and is calculated as the length of the roadway segment divided by

the travel time to traverse that length of roadway.

Traffic Density: Traffic density is defined as the number of vehicles occupying a length of roadway, usually specified as one mile. Traffic density is computed by dividing the rate of traffic flow by the average travel speed exhibited on a given lane or road section. This measure is expressed in units of passenger cars per mile per lane.

Maximum Service Flow: This measure is the highest **15-minute** rate of traffic flow that can be accommodated on a freeway under ideal conditions, while maintaining operating characteristics such as speed for a given LOS. Maximum service flow rates are expressed as passenger cars per hour per lane.

Volume-to-Capacity Ratio: This measure is derived by dividing the volume of traffic on a road by the capacity of the road to carry traffic. Ratios ranging from 0.70 to 1.00 have been used as indicators of congested traffic flow conditions.

Average Daily Traffic (ADT): This measure is the aggregation of all vehicles that pass over a given lane or road section in a given time period.

Daily Vehicle Miles of Travel (DVMT): This is a systemwide measure that is derived by averaging total miles of travel by all vehicles during a day across all road sections.

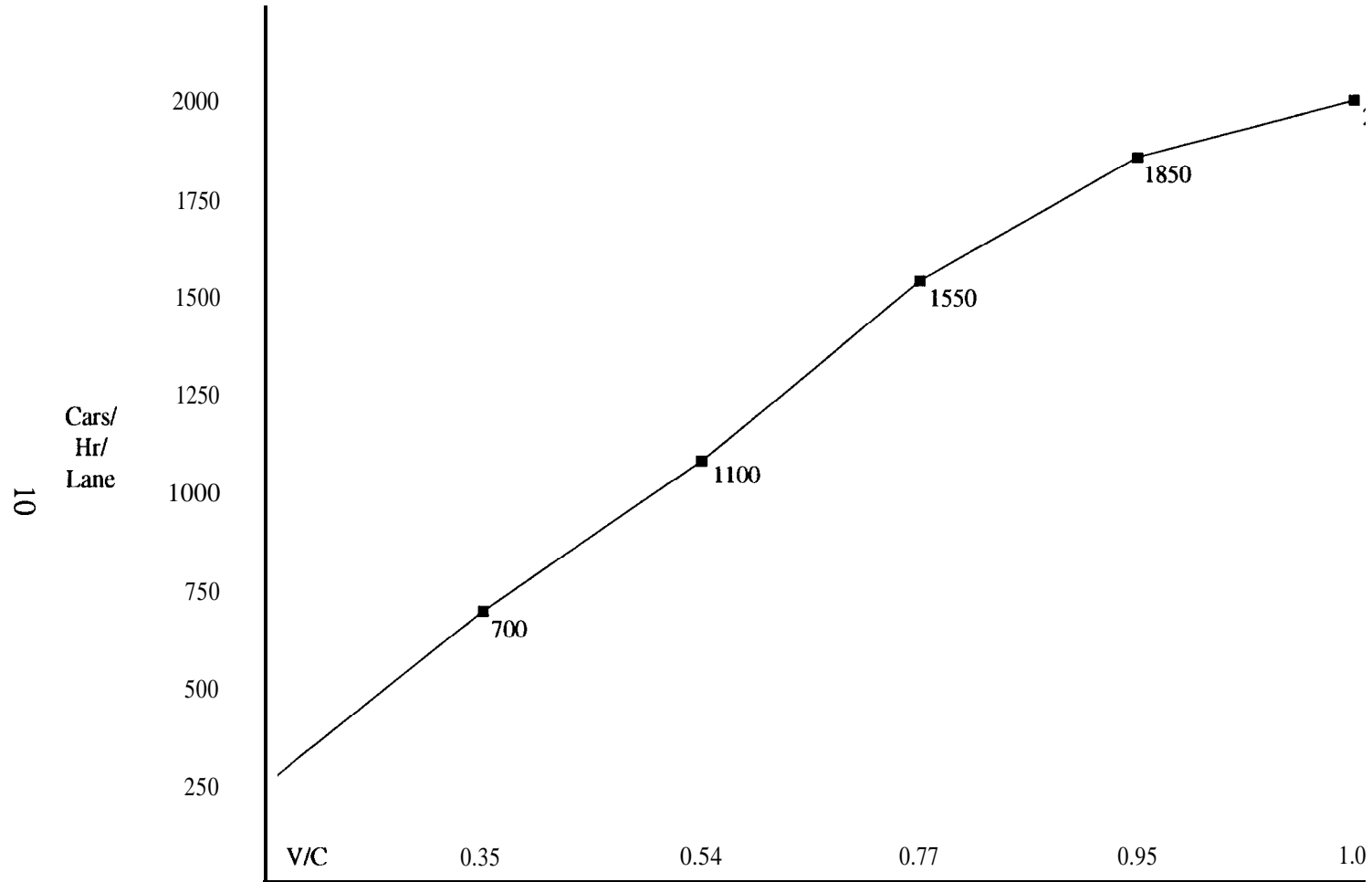
Figure 1 shows on all these measures on a common scale to show their interconnections.

K-Factor: Another measure from the HCM is the systemwide K-factor that has been suggested as an indicator of congestion. The K-factor is the percentage of average annual daily traffic (AADT) occurring during the peak hour, a two-way indicator of volume.

### **2.3.3 Direct Measures**

Travel Time and Speed: Travel time and speed are fundamental measurements of the traffic performance of the highway system. Several techniques exist to collect travel time data. The most direct way of obtaining this data for several vehicles between two points in the highway system is by recording the time of entry and the time of exit for individual vehicles traversing the study section, assuming that the vehicles do not make an intermediate stop. A second type of travel time study methodology is the test vehicle or floating car technique. What usually occurs is that a vehicle is placed in the traffic stream and

**Figure 1**  
**Congestion Measure Interconnections**



|                      | A  | B         | C         | D         | E      |
|----------------------|----|-----------|-----------|-----------|--------|
| LOS                  | A  | B         | C         | D         | E      |
| Density (cars/mi/ln) | 12 | 20        | 30        | 42        | 67     |
| DVMT                 | *  | 11,500    | 13,000    | 15,000    | 17.0   |
| ADT                  | *  |           |           |           |        |
| Speed                | 60 | 13,000 57 | 15,000 54 | 17,000 46 | 18,500 |

\* = No values given at this level of service.  
Source: Pisarski, Alan E.

instructed to travel as an “average” vehicle. Caltrans uses this data collection method in several of its most heavily congested urban area districts.

Travel Delay: Delay is defined (Transportation Research Board, 1985) as the additional time experienced by a driver beyond what would reasonably be desired for a given trip. Corresponding to the two types of congestion (recurring and non-recurring), there are two types of delay, that caused by recurring congestion and non-recurring congestion. Various methodologies are used to estimate delay employing different thresholds for the beginning of delay, resulting in estimates which vary considerably. The major methodologies used to derive delay are discussed in Section 3.

#### **2.3.4 Indirect Measures**

Throughput: Two different definitions of throughput have been defined in the literature. One definition expresses throughput as traffic volume, in terms of the number of vehicles. With this definition, factors such as the number of travel lanes and facility capacity could affect throughput. Another definition defines throughput as the number of persons per hour passing through a corridor. The second definition for throughput is commonly used to compare the effectiveness of HOV lanes against adjacent conventional mixed-flow lanes.

Congestion Severity Index (CSI): This measure was derived from research conducted at the Federal Highway Administration (FHWA) to estimate the relative congestion levels across urban areas in the United States (Lindley, 1987b). The CSI is calculated simply as the total delay per million vehicle miles of travel. Both recurring and non-recurring types of congestion were incorporated into the derivation of total delay. The analysis assumed a threshold of congestion to begin at a V/C ratio of 0.77 or greater (LOS D or worse). This research is discussed in more detail in Section 3.1.

Roadway Congestion Index (RCI): This measure was derived from research conducted at the Texas Transportation Institute (TTI) to quantify the relative congestion levels in urban areas (Lomax and Christiansen, 1982; Lomax, Bullard and Hanks, 1988; Hanks and Lomax, 1989, 1992). The RCI is an empirically derived formula that combines DVMT per lane-mile or roadway for both freeways and principal arterial streets. The RCI equation weighs the



DVMT per lane-mile values for the two facility types by their respective amount of DVMT, which is then normalized by DVMT per lane-mile values representing the threshold of congestion (LOS D or worse). Once normalized, RCI values greater than 1.0 represent undesirable average congestion levels within an urban area. This research is discussed further in Section 3.2.

Lane-Mile Duration Index (LMDI<sub>F</sub>): This measure was derived from research performed at the FHWA to estimate the extent and duration of recurring freeway congestion in urban areas (Cottrell, 1991). The LMDI<sub>F</sub> value for each urban area is the sum of the product of congested lane-miles and congestion duration (hours) for individual roadway segments, and is calculated using the average annual daily traffic volume per hourly capacity (AADTK). A V/C ratio greater than 1.0 (LOS F), or AADT/C ratio greater than 9.0 represented the start of congested travel conditions.

### **3. QUANTIFYING THE COSTS OF TRAFFIC CONGESTION**

As described in Section 2, the price being paid for roadway traffic congestion is substantial. This section describes major attempts to quantify the many and varied costs of congestion. A result of previous inquiries has been, unfortunately, the inability to quantify all aspects of these congestion costs. Based on the endeavors to quantify congestion costs, the added travel time delay has been the most tractable entity to quantify and is the primary cost component. There remains, however, the question to what extent would the to-date unquantified aspects of congestion costs contribute to the total bill could they be quantified?

#### **3.1 Federal Highway Administration**

In 1986 the FHWA embarked on a study conducted by Jeffrey Lindley to quantify the costs of urban traffic congestion as a result of the immediate seriousness of the problem, the importance of it as a long-term traffic research issue and the lack of any method for quantifying either the size of the problem or its projected future growth. Information sources reviewed to assess this congestion cost quantification approach consist of the

following: (FHWA, 1986), (FHWA, 1987), (Lindley, 1986), (Lindley, 1987a), (Lindley, 1987b), (Lindley, 1988), (Lindley, 1989), and (U.S. General Accounting Office, 1989).

### **3.1.1 Research Summary**

While the study considers quantifying congestion on both freeways and arterials, published estimates for freeways only were available. Thus, the focus in this report is on urban area freeways. The components of congestion investigated were the delay caused by vehicles traveling under less than optimal free-flow conditions under both recurring and non-recurring congestion, and one component of the inefficiency in vehicle operations, namely, wasted fuel.

The source of data used in the delay derivation was the Highway Performance Monitoring System (HPMS) database maintained by the FHWA and annually updated with state-supplied information. The HPMS database contains detailed geometric, traffic, and other data for approximately fifty percent of the urban freeway mileage in the nation. The database may be used to represent the total urban freeway system with the use of approximate expansion factors supplied by each state. The data required by the methodology are as follows: (1) roadway segment length, (2) number of lanes, (3) Annual average daily traffic (AADT), (4) K-factor, (5) D-factor (peak hour directional percentage), (6) width of lanes, and (7) roadway segment truck percentage.

The methodology is outlined as follows and was performed on individual segments of freeways.

#### Delay from recurring congestion:

- Calculate capacity based on number of lanes, an adjustment factor for lane width, lateral clearance, the presence of trucks, and type of terrain, and a value of 2,000 vehicles per lane per hour for the basic lane capacity assuming a roadway design speed of at least 60 miles per hour (mph).
- Assign a 24-hour traffic volume profile. Numerous 24-hour traffic volume profiles were developed from data obtained from traffic counts at several locations on two Washington D.C. area freeways (Interstates 66 and 395). The data obtained from these two roadways represented a variety of peak-hour traffic percentages (K-factor) and directional factors (D-factor), from which twelve 24-hour traffic volume profiles were

derived.

- Calculate total annual vehicle miles of travel based on AADT and roadway section length.
- Calculate volume-to-capacity ratio (V/C) for each hour of a typical day based on AADT, K-factor, and D-factor.
- Determine which hours of the day are to be classified as congested. A V/C ratio of 0.77 was used to indicate the onset of congested travel conditions (boundary between LOS C and LOS D).
- Calculate total annual congested vehicle miles of travel based on AADT, roadway section length, and percentage of daily traffic experiencing congested conditions, which is the sum of the percentages of traffic occurring during those hours of the day with a V/C ratio greater than or equal to 0.77.
- Calculate annual vehicle hours of delay based on AADT, percentage of daily traffic experiencing congested conditions, ideal section travel time per vehicle (average speed = 55 mph), and actual section travel time per vehicle calculated from speed-volume relationship documented in HCM. This calculation was performed for each hour of congested travel. Actual hourly section travel time is the reciprocal of actual hourly section travel speed (estimated from the HCM and the associated V/C ratio value) multiplied by the route segment length.

Excess fuel consumption from recurring congestion:

- Calculate actual fuel efficiency (mile per gallon) under congested conditions and ideal fuel efficiency under free-flow conditions from the following linear regression model:

$$\text{Equation 1: Average fuel efficiency (mpg)} = 8.8 + 0.25 \times (\text{Average speed})$$

- Calculate excess fuel consumption (gallons per mile).
- Calculate total excess fuel consumed (gallons) by multiplying excess fuel consumption by the length in miles of the roadway segment.

This methodology was based on work in (Raus, 1981).

Delay from non-recurring; congestion:

- Calculate total incident rates associated with freeways with adequate shoulders and with no shoulders.

- Develop incident trees for each freeway type (with shoulders, with no shoulders) with percentages for each branch. With shoulders: (1) location (in-lane, shoulder), (2) incident type (accident, disablement), and (3) number of lanes affected. Without shoulders: (1) incident type and (2) number of affected lanes.
- Calculate number of occurrences per year of each incident type for each hour of the day based on incident trees.
- Calculate time until normal traffic flow or flow under expected traffic demand patterns resumes based on freeway capacity, traffic volume, and incident duration times.
- Calculate delay caused by the presence of an incident for each incident type.
- 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.

This methodology was based on work documented in (Owen and Urbanek, 1978).

Excess fuel consumption from non-recurring congestion:

- Calculate excess fuel consumption based on same linear regression relationship between fuel efficiency and average speed used previously for calculating excess fuel consumption from recurring congestion. Excess fuel consumption for non-recurring congestion is calculated for each of the freeway sections where delay due to incidents occurs.

This methodology was based on work documented in (Raus, 1981).

Total user costs (\$):

Congestion has thus far been quantified in terms of added delay (hours) and excess fuel (gallons of fuel). The final step in quantifying the costs of congestion is to express these two component costs in terms of their dollar value. The hourly value of time (\$/vehicle-hour) was calculated from (1) value-of-time estimates of delay for average urban freeway work trips (\$/traveler work trip hour), (2) the Consumer Price Index, and (3) average vehicle occupancy. The dollar value of excess fuel was estimated by multiplying the amount of excess fuel (gallons) by the cost of fuel (\$/gallon).

### 3.1.2 Review Of Methodological Approach

The methodology developed by Lindley depended on numerous factors including assumptions, available data sources, and specific analytical techniques that are presently reviewed.

Threshold for congestion: The derivation of delay depended on the threshold of congestion used. The FHWA model used 0.77 V/C ratio and the corresponding value of 54 mph average speed as threshold markers for traffic congestion. Various congestion thresholds are used by MPOs and transportation agencies, in particular the California Department of Transportation (Caltrans). Caltrans considers a roadway to be congested when its V/C ratio is approximately 1.00 with an associated average travel speed of 35 mph or less. Caltrans' estimation of delay is more fully discussed in Section 3.4. This threshold is not a universally accepted value and since congestion is a qualitative term, it readily lends itself to numerous starting points.

In fact, in 1991, the FHWA completed additional research in the area of quantifying congestion. The focus of this work was on recurring congestion on urban area freeways and the development of a congestion indicator combining both the duration and extent of congestion in a single measure (Cottrell, 1991), (Texas Transportation Institute, 1992), and (Epps et al. 1993). The only impact of congestion considered in this work was recurring congestion-induced delay expressed in terms of both its duration and physical extent by a newly developed indicator called the lane-mile duration index. The purpose of developing this congestion indicator was to compare recurring congestion experienced in urban areas. Primary use of this methodology is aimed for planning applications. The primary difference between the estimation of total hours of delay from this work and Lindley's research is the threshold of congestion. Cottrell assumed a V/C ratio greater than 1.0 (LOS F) associated with an average travel speed of no greater than 30 mph to represent the onset of congested travel conditions. This congestion threshold more closely resembles that of Caltrans. A sensitivity analysis of Lindley's model's output under alternative input values for the V/C ratio was performed as part of a review the General Accounting Office did (U.S. General Accounting Office, 1989) and found that the model was relatively insensitive to changes in

the V/C ratio. The range in percentage change in total delay (vehicle hours) given a change in V/C ratio from 0.77 to 0.99 and variability in other parameter values was 4.2 % to 6.8 % .

Traffic volume profiles: Twelve 24-hour traffic volume profiles were derived from traffic counts on two specific Washington D.C. freeways and form the basis of all subsequent analysis. The prime issue (U.S. General Accounting Office, 1989) is whether these resulting profiles are characteristic of urban area freeways throughout the United States. The FHWA claimed these profiles were similar in shape to profiles developed with traffic volume data from interstates in other metropolitan urban areas and so supported the use of these profiles. The General Accounting Office (GAO) did not, however, investigate this matter further, i.e. by performing sensitivity analyses on alternative profiles, to resolve the outstanding question of traffic volume profile representativeness.

Response of Drivers: The model did not consider drivers' response to congested traffic conditions. The model assumes, contrary to some professional opinion, that drivers do not show any tendency to divert to alternative routes as traffic conditions continue to worsen, which would tend to overstate the congestion problem.

Roadway Capacity: In addition to the quantification of the currently existing congestion problem, forecasts were made of the long-term effects of congestion. The model assumed, however, that there will be no change in the transportation supply, i.e. no additions to capacity. Capacity increases, e.g. through new construction and improvements may induce traffic as people choose to make trips they formerly would have foregone because of excessive congestion. This increase in traffic tends to occur over the longterm, i.e. two decades. Moreover, even after many years, traffic induced by capacity increases is considerably less than what would be required to produce the same V/C ratios in the absence of the capacity enhancement project (Dobbins, A. et al, 1994).

A sensitivity analysis of this model's output under alternative input values for roadway capacity was performed as part of a review the GAO did (U. S . GAO, 1989) and found that the model was very sensitive to changes in capacity. The range in percentage change in total delay (vehicle hours) given a percentage increase in capacity up to 40% with all other variables held constant was between 40 % and 50%.

HPMS Database Limitations: Although the HPMS database is considered a statistically

valid representative sample of the nation's freeways, some of the state-supplied data on K-factors, D-factors, and section capacities may be erroneously coded or simply inaccurate. In addition, actual freeway mileage for particular metropolitan areas may be inaccurate since states have freedom in the way they sample their urban freeway sections. Finally, the variability in the methodology across individual states could pose a problem in comparing congestion across certain urban areas.

## **3.2 Texas Transportation Institute**

In 1982 researchers at the Texas Transportation Institute (TTI) embarked on a multi-year investigation of congestion and quantifying its costs in all major Texas cities as well as numerous other cities around the United States. Information sources reviewed to assess this congestion cost quantification approach consist of the following: (Lomax et al, 1982), (Lomax et al, 1988), (Hanks et al 1989), and (Hanks et al, 1992).

### **3.2.1 Research Summary**

While the study considered quantifying congestion on both freeways and arterials, the focus was on urban area freeways. The components of congestion investigated were the delay caused by vehicles traveling under less than optimal free-flow conditions under both recurring and non-recurring congestion, one component of the inefficiency in vehicle operations, specifically, wasted fuel, and increased insurance premiums.

The source of data used in the delay derivation was the Highway Performance Monitoring System (HPMS) database as in the case of the previously described FHWA research and supplemented as required by local planning and transportation agencies and state departments of transportation.

The methodology is outlined as follows and was performed on individual roadway segments. The boundary between LOS C and LOS D was used as the threshold for the beginning of congestion. This is consistent with work performed by FHWA, in which V/C ratio was used as the prime measure of congestion with a value of 0.77 as the threshold of

congestion. However, daily volume of vehicles per lane was used as the prime congestion measure instead of V/C ratio.

Delay from recurring congestion:

- Estimate the daily volume of vehicles per lane corresponding to a V/C ratio of 0.77 to derive the threshold of congestion, namely 15,000 vehicles per lane per day. (for freeways)
- Calculate Daily VMT (DVMT) for each roadway section as the average daily traffic (ADT) of a section of roadway multiplied by the length (miles) of that section of roadway.
- Estimate the percentage of ADT occurring during the peak periods based on data collection on freeways in major Texas metropolitan areas.
- Estimate DVMT congestion factor, the percentage of daily travel operating under congested conditions. This factor is defined as the sum of DVMT occurring on each roadway segment with ADT greater than the congestion threshold value (15,000 ADT/lane) divided by the total DVMT.
- Calculate peak-period congested DVMT as the product of DVMT, the percentage of ADT occurring during the peak periods, and DVMT congestion factor.
- Determine average freeway speeds based on data collected from travel time and speed surveys in Texas. Peak and off-period average freeway speeds are 35 mph and 55 mph respectively.
- Calculate daily recurring vehicle-hour delay by the following formula:

Equation 2:

$$\frac{\text{Recurring Vehicle-hour Delay}}{\text{Day}} = \frac{\text{Peak-period Congested DVMT}}{\text{Avg. Peak-period speed}} - \frac{\text{Peak-period Congested DVMT}}{\text{Avg. Off-peak speed}}$$

Excess fuel consumption from recurring congestion:

- Calculate average fuel efficiency (mpg) using the same methodology as used by Lindley .
- Calculate total excess fuel (gallons) used as a result of recurring delay using the following formulas:



Equation 3 :

$$\text{Passenger Fuel Cost} = \frac{\text{Daily VHD} \times 95\% \times \text{Average Speed}}{\text{Average Fuel Efficiency}}$$

Equation 4:

$$\text{Commercial Fuel Cost} = \frac{\text{Daily VHD} \times 5\% \times \text{Average Speed}}{\text{Average Fuel Efficiency}}$$

The placement of "95 %" and "5 %" into the above formulas reflects the vehicle fleet percentage mix of passenger and commercial vehicles, respectively.

Delay from non-recurring: congestion:

- Calculate vehicle hours of delay due to incidents by the following formula:

Equation 5 :

$$\text{Daily Non-recurring VHD} = \text{Daily Recurring VHD} \times \frac{\text{Non-recurring/recurring ratio}}{\text{Non-recurring/recurring ratio}}$$

Non-recurring/recurring ratio is based on results from (FHWA, 1986).

Excess fuel consumption from non-recurring: congestion:

- Methodology used to calculate excess fuel consumption from recurring congestion was used in the case of non-recurring congestion.

Insurance cost:

- Calculate insurance cost by multiplying the insurance rate differential by the number of registered vehicles within the area under investigation, according to the following formula:

Equation 6:

$$\text{Excess insurance cost per year} = \frac{\text{Study area-State Rate}}{\text{Rate}} \times 0.7 \times \text{Number of registered vehicles}$$

The factor 0.7 is the approximate percentage of an insurance premium used to provide insurance coverage for the vehicle. Thirty percent of the premium was estimated to be used for overhead coverage’.

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<sup>1</sup>The auto insurance rates represent the state and urban area averages. These rates were compiled by averaging the rates for the minimum required automobile coverage for a married male over the age of twenty-five years in the various areas and states as quoted

### Total user costs (\$):

- Same methodology as used by Lindley was used to convert total hours of delay and excess fuel into dollars.

### **3.2.2 Review Of Methodological Approach**

The methodology developed by TTI depended on numerous factors including assumptions, available data sources, and specific analytical techniques that are presently reviewed.

Threshold for congestion: The derivation of delay depends on the threshold of congestion used. The TTI methodology uses 15,000 ADT per lane as threshold markers for traffic congestion (corresponding to a V/C ratio of 0.77) (See Section 3.1.2).

Level of Aggregation: Only two values for average speed were used, peak and off-peak period in the derivation of vehicle hours of delay (See last bullet under explanation for methodology used to calculate Delay from recurring congestion in Section 3.2.1). This averaging process could result in loss of information and reduction in accuracy since aggregating all speeds into only two values does not allow for the variability in travel speeds throughout the day and so does not reflect the true travel speed profile in the calculation of delay.

Response of Drivers: As in the case of the FHWA model, this methodology did not consider drivers' response to congested traffic conditions. The model assumes, contrary to some professional opinion, that drivers do not show any tendency to divert to alternative routes and traffic conditions continue to worsen, which would tend to overstate the congestion problem.

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by three major insurance carriers. The statewide rate is the overall state average rate excluding the study areas and other large urban areas. This procedure allowed the calculation of the additional insurance premiums paid by motorists operating vehicles in large urban areas. These costs do not include commercial vehicles because of the wide variance in rates and the difficulty in identifying the registered commercial vehicles actually operating within that particular area.

HPMS Database Limitations: Although the HPMS database is considered a statistically valid representative sample of the nation's freeways, some of the state-supplied data on K-factors, D-factors, and section capacities may be erroneously coded or simply inaccurate. In addition, actual freeway mileage for particular metropolitan areas may be inaccurate since states have freedom in the way they sample their urban freeway sections. Finally, the variability in the methodology across individual states could pose a problem in comparing congestion across certain urban areas.

### **3.3 Southern California Association Of Governments**

The Southern California Association of Governments (SCAG) is the designated MPO for regional transportation in the greater metropolitan Los Angeles area. SCAG is charged with developing biennial regional transportation mobility plans. In 1987, as part of this process, SCAG developed a methodology to estimate congestion costs associated with numerous regional mobility planning alternatives. Documentation reviewed to assess this congestion cost quantification approach consisted of the following: (Keegan, 1987) and (SCAG, 1988).

#### **3.3.1 Research Summary**

While the study considers quantifying congestion on both freeways and arterials, the focus was on urban area freeways. The components of congestion impacts investigated were the delay caused by vehicles traveling under less than optimal free-flow conditions under recurring congestion, and additional vehicle operating costs incurred due to congestion, resulting from use of excess fuel and oil, wear and tear on tires, additional maintenance, and depreciation. Even though conventional wisdom favors using a 50-50 percentage split between recurring and non-recurring congestion-induced delay, results presented are for recurring congestion only. The authors ((Keegan, 1987) and (SCAG, 1988)) felt the lack of complete and unequivocal information and data to accurately estimate costs due to incident delay precluded the use of the conventional wisdom method, i.e. the 50-50

percentage split.

The data used to derive estimates of delay for recurring congestion was selected output from SCAG's Regional Transportation Model (RTM) under work for development of the 1984 Regional Mobility Plan. The RTM simulates travel in urbanized portions of the SCAG region (Los Angeles, Orange, Ventura, Riverside, San Bernardino, and Imperial Counties). The selected model output provided estimates for average weekday travel (vehicle miles of travel (VMT), vehicle hours of travel (VHT), and vehicle hours of delay (VHD)) for five facility types (freeways, ramps, major arterials, minor arterials, and collector/connector roads) and three time periods (6:30-8:30 A.M., 3:00-6:00 P.M., and off-peak periods<sup>2</sup>). The five facility types were aggregated into two types: freeways (freeways and ramps) and arterials (major and minor arterials and collector/connector roads).

The costs of congestion were estimated on a daily basis partitioned into personal and business costs. Personal costs were further divided into vehicular and time costs. Business costs were further divided into vehicular and labor costs. Vehicular costs were further stratified by vehicle type. Personal vehicular costs included only those associated with travel by automobile, motorcycle, and light-duty truck all aggregated into one category referred to as autos. Three types of business vehicular costs were estimated corresponding to three vehicle type categories: (1) autos (same category as in personal vehicular costs), (2) medium-duty trucks, and (3) heavy-duty trucks.

The procedure for calculating recurring congestion costs is outlined as follows:

Delay and resulting: costs from recurring congestion:

- Determine VMT and VHT by facility type and time of day. These travel measures are initially estimated on a link-by-link basis and subsequently aggregated to the level of facility type.
- Derive average travel speeds (VMT/VHT) by facility type and time of day.
- Determine VHD by facility type and time-of-day. Delay is the difference between actual travel time and free-flow travel time and is an output of the transportation

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<sup>2</sup>The off-peak periods consist of those hours of the day outside the two peak periods, i.e. 8:30 A.M.-3:00 P.M. and 6:00 P.M. to 6:30 A.M.

model. Free-flow travel time corresponds to free-flow travel speed at 55 mph. Delay is initially estimated by link then aggregated to the level of facility type.

- Stratify VHD by trip types (personal and business).
- Stratify VHD by vehicle type for each trip type.
- Derive dollar value of time for both personal and business trips.
- Calculate total costs associated with additional delay by trip type (dollar value of time x VHD).

#### Vehicular costs from recurring congestion:

- Derive daily congested vehicle miles of travel (average travel speed x VHD) by facility type, time of day, trip type, and vehicle type. Congested VMT is also referred to as vehicle miles of delay.
- Derive vehicle operating costs expressed per 1,000 miles of travel by vehicle type.
- Derive total vehicle operating costs (vehicle operating costs per 1,000 miles of travel x daily vehicle miles of delay (in 1,000s)).

### **3.3.2 Review Of Methodological Approach**

The methodology developed by SCAG depended on numerous factors including assumptions, available data sources, and specific analytical techniques that are presently reviewed.

Recurring vs. non-recurring congestion: The authors had no reliable information with which to estimate non-recurring congestion and would have had to accept conventional wisdom and use the generally accepted 50-50 percentage split. They chose instead to focus on recurring congestion only. A methodology does exist to estimate non-recurring delay and was used by Lindley in his research (Section 3.1). Moreover, a substantial research effort is underway at the University of California at Berkeley, Institute of Transportation Studies developing an implementable methodology for quantifying non-recurring freeway congestion delay (Epps et al. 1993).

Actual travel data vs. model output: SCAG's RTP model was the prime source of data used

in the estimation of the costs of congestion. Moreover, inputs to the model were based on data that was substantially dated (1967 Origin-Destination Survey). Since the task was to estimate congestion, using potentially outdated information could place considerable doubt on the accuracy of the results. For modeling purposes the SCAG region is divided into approximately 1325 zones. Trips may be considered interzonal or intrazonal in nature. Intrazonal freeway trips are not accounted for in the model and thus can lead to an underestimation of congestion-induced delay.

Exclusion of transit: Due to a lack of information, trips taken by bus were not included in the analysis. Since the use of transit would tend to dampen the effects of congestion, its exclusion probably led to an overestimation of congestion-induced delay.

Derivation of vehicle operating costs: The methodology used to estimate vehicle operating costs involved cost data expressed in terms of 1,000s of vehicle-miles traveled. This resulted in the need to estimate the VMT under congested travel conditions. The authors formed a new quantity called congested vehicle miles of travel, also referred to as vehicle miles of delay as the product of average speed and vehicle hours of delay. This new entity was estimated for each facility type, time of day, and vehicle type. Its derivation and use is a misapplication of the speed-distance-time relationship. The goal was to derive a congestion measure in units of distance of travel. After deriving total VMT by facility type, the question was what percentage of each facility type's total travel (VMT) operates under congested conditions? Before the model's output is aggregated over all links for a particular facility type, the following link output data is available for each of the three time periods: (1) number of lanes, (2) link length, (3) traffic volume, (4) V/C ratio, (5) VMT, (6) VHT, and (7) average speed. It seems that a method similar to that developed by Lindley , i.e. the percentage of daily traffic experiencing congested conditions, could be developed in this work. However, instead of having hourly information for each link, only three time-periods worth of data are available.

### **3.4 Caltrans**

Caltrans' Headquarters has instituted a program called Highway Congestion Monitoring

Program (HICOMP) to monitor congestion on urban area freeways. Recurring congestion-induced delays have been estimated for several years through the use of HICOMP. Delays due to non-recurring congestion have not been directly measured, but are assumed to comprise approximately 50% of total congestion. A research effort is underway at the University of California at Berkeley, Institute of Transportation Studies to develop a methodology for quantifying non-recurring freeway congestion delay (Epps et al. 1993).

HICOMP reports that document the measurement of recurring congestion are submitted by seven of the twelve most urbanized and heavily congested Caltrans' districts (District 3 = Sacramento area, District 4 = San Francisco Bay Area, District 6 = Fresno area, District 7 = Los Angeles/Ventura area, District 8 = Riverside/San Bernadino, District 11 = San Diego area, and District 12 = Orange County). Other districts measure congestion, such as District 5 in the Santa Barbara/San Luis Obispo area though have not been required to submit written documentation. This may change as congestion worsens in those districts. Data is collected twice a year, in the Spring and Fall. The winter's inclement weather and the summer's changing travel patterns due to vacations and tourism precludes these times of the year for data collection. Data is collected for peak periods only (morning and afternoon) during incident-free mid-week days (Tuesday, Wednesday, and Thursday). Mondays and Fridays are excluded to minimize the influence of weekend travel plans. An incident occurring during data collection makes that entire data collection unusable.

Congestion is defined as a condition where the average speed drops below 35 mph for 15 minutes. The delay associated with congestion is defined as the difference in travel time between 35 mph and the lower speed.

Two methodologies are currently in use to collect data. Six of the seven Caltrans' districts (3, 4, 6, 8, 11, 12) submitting HICOMP reports use tachometer runs to obtain data for monitoring recurring congestion. This method is also referred to as the "floating car" method for data collection. Vehicles equipped with laptop computers traverse congested segments of the freeway system, emulate "average" traffic flow behavior, and collect speed and distance information for the entire duration of congestion. Two tachometer runs (morning and afternoon peak periods) for each of the two data collection periods (Spring and Fall) conducted under normal recurring congestion conditions, i.e. no incidents, are the

minimum number of observations obtained. Delay is calculated from this field data. District 7 currently uses loop detectors to obtain data for monitoring recurring congestion. Numerous types of measurements can be made with a single detector. Microscopic traffic flow characteristics that can be obtained through direct measurement or estimation consist of (1) time headway between vehicles, (2) lane occupancy time, (3) vehicle speeds, and (4) distance headways. Macroscopic traffic flow characteristics can be estimated from the microscopic traffic flow characteristics and include (1) flow rate (vehicles per hour), (2) average traffic speed (time mean speed), and (3) traffic density (May, 1990). In addition, speed contour maps may be produced which are used to estimate delay.

### **3.5 Discussion Across Alternative Studies**

Differences in methodological approach including required data and simplifying assumptions make the investigated efforts at quantifying congestion neither entirely, directly, nor easily comparable. There are, however, components that are analogous and are examined further.

#### **3.5.1 Extent Of Quantification**

As indicated in Section 2.2, there are numerous impacts of congestion, consisting of additional time spent on congested roadways, the added vehicle operating costs due to driving under congested conditions, reduction in levels of comfort and convenience, reduced safety, automobile insurance premium increases, health impairment, constraints on economic growth, loss of transportation system efficiency, and environmental damage. A summary of the congestion impacts quantified is in Table 1. Other congestion impacts were not quantified because of difficulty in at least one phase of the quantification process, namely, developing a methodological approach or obtaining data. While it is desirable to obtain as complete a profile as possible of the costs of congestion, delay may continue to be the dominant component, in terms of dollar amount, relative to the other components of congestion costs. Delay plays a very substantial portion for each of the quantification efforts



that did assign a dollar value to the congestion costs (FHWA, TTI, SCAG) (See Table 2). There remains, however, the question to what extent would the to-date unquantified aspects of congestion costs contribute to the total bill could they be quantified?

**TABLE 1**  
**SUMMARY OF QUANTIFIED CONGESTION IMPACTS**

Quantified Congestion Impacts

|                 |  |
|-----------------|--|
| FHWA (Lindley)  | <ul style="list-style-type: none"> <li>● Delay (recurring and non-recurring)</li> <li>● Vehicle Operations (fuel)</li> </ul>                                 |
| FHWA (Cottrell) | <ul style="list-style-type: none"> <li>● Delay (recurring)”</li> </ul>   |
| TTI             | <ul style="list-style-type: none"> <li>● Delay (recurring and non-recurring)</li> <li>● Vehicle Operations (fuel)</li> <li>● Automobile Insurance</li> </ul> |
| SCAG            | <ul style="list-style-type: none"> <li>● Delay (recurring)</li> <li>● Vehicle Operations (fuel, oil, tires, maintenance, depreciation)</li> </ul>            |
| CALTRANS        | <ul style="list-style-type: none"> <li>● Delay (recurring and non-recurring)<sup>a</sup></li> </ul>  |

<sup>a</sup>Dollar value was not assigned to total vehicles-hour-of-delay.

**3.5.2 Explanation Of Conflicts Among Studies**

As stated previously, numerous differences exist among the studies under investigation resulting in conflicts among estimates of congestion costs. This section will examine these differences and account for as many of the conflicts as possible to facilitate a valid comparison of congestion costs across studies.

The examination includes an inquiry into the following studies: FHWA (Lindley), TTI, SCAG, and Caltrans. The work by Cottrell (Cottrell, 1991) did not contain sufficient data to perform further analysis. Even though Caltrans’ work does not estimate the dollar value

of congestion, it does estimate delay and is short only the final set of arithmetic steps (multiplication by dollar value of time and vehicle occupancy) to convert delay (hours) into dollars. Caltrans' work is thus also considered in the following analysis.

TABLE 2  
CONTRIBUTION OF DELAY TO TOTAL COSTS OF **CONGESTION**<sup>a</sup>

|                |                            |
|----------------|----------------------------|
| FHWA (Lindley) | 74.0%-86.2% <sup>bcd</sup> |
| TTI            | 44.1 %-84.6% <sup>ef</sup> |
| SCAG           | 57.7%-71.6% <sup>gh</sup>  |

<sup>a</sup>Extent of comparability across studies is very limited due to differences in assumptions, data, methodologies, and congestion impacts that are quantified. Contribution of delay is nonetheless quite significant for all studies. Understanding conflicts among the various studies is addressed in Section 3.5.2.

<sup>b</sup>Range accounts for variability over 37 U.S. urban areas with populations greater than one million persons. Cost statistics are for 1984 freeway estimates.

<sup>c</sup>Percentage contribution for delay in 35 of the 37 urban areas varies between 81 .0 and 86.2 percent.

<sup>d</sup>Percentage contribution of delay over whole nation is 85 .0% .

<sup>e</sup>Range accounts for variability over 29 Western and Southern U.S. urban areas with populations greater than 250 thousand persons, sixty percent of which have populations over one million persons.

<sup>f</sup>Percentage contribution for delay in 24 of the 29 urban areas varies between 61.5 and 84.6 percent.

<sup>g</sup>Range accounts for variability over facility type (freeway and arterials) and time-of-day (A.M.,P.M.,and off-peak periods). Cost statistics are daily estimates based on 1984 input data.

<sup>h</sup>There is no change from daily to annual percentage contribution of delay.

Spatial Scope: These studies' spatial scope is considered initially. FHWA's and TTI's work covers numerous U.S. urban areas. Each of these two studies considers four of California's most heavily congested urban areas, namely Los Angeles, San Francisco, San Diego, and Sacramento. Even though the SCAG study examines only the Los Angeles

region, all four of California's most congested regions are considered since the other three regions are considered by the FHWA, TTI, and Caltrans analysis.

Congestion Impacts Quantified: Recurring delay is the only impact of congestion common to all four studies, however, recurring and non-recurring delay is common to FHWA, TTI, and Caltrans' analysis. Differences due to which impacts are quantified can contribute significantly to the differences among the studies.

Facility Type: Freeways are the only facility type considered by all four studies. The TTI and SCAG analyses quantify congestion costs relative to freeways and arterials. The FHWA develops a methodology for quantifying delay on both freeways and arterials, however, data for arterials is insufficient for use here.

### 3.5.2.1 Comparative Analysis

This section compares the following estimates across studies: (1) daily recurring delay for all four studies relative to the Los Angeles area for **freeways**<sup>3</sup>, and (2) daily recurring and non-recurring delay for the FHWA, TTI and Caltrans' studies relative to three congested urban regions in California (San Francisco, San Diego, and Sacramento) for freeways (See Table 3).

Recurring Delay: Caltrans recurring delay statistics are substantially less than FHWA and TTI for the following two reasons: (1) Caltrans delay estimates are based on traffic during the morning and afternoon peak periods. While these two time periods account for a substantial portion of the daily congestion, A.M. peak and P.M. peak may not be only period of time for which travelers experience congested road conditions; (2) the threshold of congestion used by Caltrans is 35 mph. Thus traffic flowing between 36 mph and 54 mph is not considered driving under congested conditions, whereas it is considered congested conditions under both FHWA's and TTI's methodology resulting in less delay under the Caltrans calculation. Moreover, for congested traffic flowing at less than 35 mph, delay is

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<sup>3</sup>Data for all four studies was available only for recurrent delay for the Los Angeles area.

**TABLE 3**  
**COMPARISON OF ESTIMATES FOR DAILY**  
**RECURRING AND NON-RECURRING DELAY FOR FREEWAYS**  
**(1,000s vehicle hours)<sup>a</sup>**

|                 | Urban Areas   |                |                     |                     |                     |                     |             |                     |
|-----------------|---------------|----------------|---------------------|---------------------|---------------------|---------------------|-------------|---------------------|
|                 | San Francisco |                | San Diego           |                     | Sacramento          |                     | Los Angeles |                     |
|                 | <u>Rec</u>    | <u>Non-Ret</u> | <u>Rec</u>          | <u>Non-Ret</u>      | <u>Rec</u>          | <u>Non-Ret</u>      | <u>Rec</u>  | <u>Non-Ret</u>      |
| FHWA (1984)     | 291.6         | 382.4          | 34.4                | 20.4                | 16.8                | 10.0                | 313.2       | 378.8               |
| TTI (1986)      | 129.5         | 168.4          | 39.3                | 23.6                | 10.4                | 6.2                 | 366.0       | 439.2               |
| Caltrans (1988) | 58.6          | 58.6           | 12.9                | 12.9                | 1.4                 | 1.4                 | 87.5        | 87.5                |
| SCAG<br>(1984)  | <sup>b</sup>  | <sup>b</sup>   | <u><sup>b</sup></u> | <u><sup>b</sup></u> | <u><sup>b</sup></u> | <u><sup>b</sup></u> | 311.7       | <u><sup>c</sup></u> |

<sup>a</sup>Based on data from the following sources: (Lindley, 1987b), (Lomax, Bullard, and Hanks, 1988), (Caltrans, 1992), (Keegan, 1987), and (SCAG, 1988).

<sup>b</sup>Region is outside the SCAG boundaries

<sup>c</sup>Non-recurring delay estimates were not calculated by the SCAG study

estimated based on comparing actual travel time relative to the travel time corresponding to 35 mph, whereas, for both FHWA and TTI, 55 mph is considered the uncongested reference speed with which actual travel speeds are measured and delay is calculated. This difference in reference speeds also contributes to a smaller Caltrans delay estimate. Caltrans delay estimates are for 1988 and FHWA and TTI are for earlier years, and all else being equal, Caltrans' delay estimates would tend to be greater than the other two since there is a general upward trend in congestion levels over time. The effect in this case is to reduce the difference in delay estimates between the other two studies and Caltrans' estimates. However, such trends could be mitigated by the fact that the span of four years is relatively short and long term trends are not without their occasional aberrations. Such phenomena as long term trends and short term deviations from those trends should be kept in mind when interpreting these results.

FHWA and TTI methodologies are basically the same and one would assume this would lead to very similar results. The primary difference between the two methodologies is that the FHWA study calculated delay for each roadway section for hours of the day experiencing congested conditions after calculating travel speed for such hours. Delay estimates were subsequently added over all relevant roadway sections. The TTI analysis similarly identified those roadway sections experiencing congested conditions, then first aggregated over all roadway sections the associated congested DVMT, then applied a single average congested speed (35 mph) to complete the delay estimation process. The TTI assumption at work here is that using the average speed will neither overestimate nor underestimate the delay.

The differences between FHWA and TTI estimates for San Francisco, San Diego, and Sacramento are mainly due to differences in the definition of the geographic region under consideration, either in terms of area or total number of center-line freeway miles. There is insufficient information to determine whether or not both studies have defined each region's land area the same way. There are, however, differences in total number of center-line miles for each region (Table 4). If the land areas were defined the same way, decreases in the number of center-line freeway miles from 1984 to 1986 for San Francisco and Sacramento would be indicative of errors of some kind, otherwise the land areas are

different. The differences in freeway mileage and accompanying delay estimates likely explains the differences in results. The passage of two years could moderate the effects of FHWA's increase over TTI's delay estimates. For Los Angeles, however, the FHWA study

TABLE 4  
TOTAL NUMBER OF CENTER-LINE FREEWAY MILES

|             | San<br>Francisco | San<br>Diego | Sacramento | LOS<br>Angeles |
|-------------|------------------|--------------|------------|----------------|
| FHWA (1984) | 602              | 157          | 130        | 647            |
| TTI (1986)  | 336              | 220          | 94         | 585            |

Source: (Lindley, 1987b) and (Lomax, Bullard, and Hanks, 1988)

considers a region with approximately ten percent more freeway mileage than does the TTI study, yet the FHWA study estimates there are approximately fourteen percent fewer vehicle hours of delay than the TTI study. It seems unlikely, though nevertheless possible, that congestion in the Los Angeles region grew between 1984 and 1986 by such an amount to account for the difference in delay estimates. FHWA and SCAG have very similar results, which could indicate that there might be an error in the published results of the TTI study.

Non-recurring Delay: Caltrans estimates non-recurring delay by assuming an equal split in total delay between recurring and non-recurring causes. The ratios of non-recurring to recurring delay for a given metropolitan area for the FHWA and the TTI studies are equal<sup>4</sup> since TTI's non-recurring delay estimates were derived directly from FHWA's methodology (FHWA, 1986). What seems evident is that the assumption of equal contribution to total delay from recurring and non-recurring components (ratio of 1) is unsubstantiated and requires further study. In fact, as previously mentioned a substantial

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<sup>4</sup>There are, however, slight differences in the recurring/non-recurring ratios between the FHWA and TTI estimates across different urban areas that are mainly due to rounding error.

research effort is underway at the University of California at Berkeley, Institute of Transportation Studies to develop an implementable methodology for quantifying non-recurring freeway congestion delay (Epps et al. 1993).

Annual User Cost Estimates: The daily delay estimates for freeway travel (Tables 3) may readily be converted into user cost estimates of congestion in units of dollars which allows for a better appreciation of the magnitude of the congestion problem. Values for vehicle occupancy, the dollar value of time, and the number of days per year when congested conditions occur are required to derive the estimates. Since both the FHWA and TTI studies used 1.25 for an estimate of vehicle occupancy and the SCAG research used an estimate of 1.22, a value of 1.25 is assumed in this research. An estimate for the value of time in 1993 dollars is based on a 1985 estimate (Chui, et al. 1987) adjusted with the Consumer Price Index (CPI) (Famighetti, 1993) and (U. S . Government Printing Office, 1994)<sup>5</sup>. The estimate in 1985 dollars, \$8 per person-hour, is adjusted to a value of approximately \$10.70 per hour in 1993 dollars. The number of days per year when congested conditions occur, i.e. the number of working days per year, is assumed to be 250 days. The relationships among the delay estimates across studies remain unchanged since each estimate was increased by the same factor. Results are presented in Table 5 and quite readily demonstrate both the magnitude and seriousness of the congestion problem even taking into account differences across the studies. It should also be recalled that these cost estimates are restricted to delay and do not reflect other congestion components which would add to the total cost of congestion.

#### **4. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK**

This section summarizes the work performed in this report, draws conclusions, and suggests next steps in this research area.

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<sup>5</sup>The World Almanac 1994 (Famighetti, 1993) provided annual percent changes in the CPI through 1992. The CPI for 1993 was provided by *Economic Indicators*, a publication of the U.S. Government Printing Office.

**TABLE 5**  
**ANNUAL USER COST ESTIMATES FOR**  
**RECURRING AND NON-RECURRING DELAY FOR FREEWAYS**  
**(millions of 1993 dollars)**

|                 | Urban Areas   |                |            |                       |            |                       |             |                       |
|-----------------|---------------|----------------|------------|-----------------------|------------|-----------------------|-------------|-----------------------|
|                 | San Francisco |                | San Diego  |                       | Sacramento |                       | Los Angeles |                       |
|                 | <u>Rec</u>    | <u>Non-Ret</u> | <u>Rec</u> | <u>Non-Ret</u>        | <u>Rec</u> | <u>Non-Ret</u>        | <u>Rec</u>  | <u>Non-Ret</u>        |
| FHWA (1984)     | 975.0         | 1,278.6        | 115.0      | 68.2                  | 56.2       | 33.4                  | 1,047.2     | 1,266.6               |
| TTI (1986)      | 433.0         | 563.1          | 131.4      | 78.9                  | 34.8       | 20.7                  | 1,223.8     | 1,468.5               |
| Caltrans (1988) | 195.9         | 195.9          | 43.1       | 43.1                  | 4.7        | 4.7                   | 292.6       | 292.6                 |
| SCAG            | (1984)        | <sup>b</sup>   | <u>b</u>   | <u>—</u> <sup>b</sup> | <u>b</u>   | <u>—</u> <sup>b</sup> | 1,042.2     | <u>—</u> <sup>c</sup> |

<sup>a</sup>Based on data from the following sources: (Lindley, 1987b), (Lomax, Bullard, and Hanks, 1988), (Caltrans, 1992), (Keegan, 1987), and (SCAG, 1988).

<sup>b</sup>Region is outside the SCAG boundaries

<sup>c</sup>Non-recurring delay estimates were not calculated by the SCAG study.



## 4.1 summary

A comprehensive understanding of the costs of roadway traffic congestion is essential to provide a substantive foundation for subsequent quantification of the benefits attributable to IVHS technologies. To improve understanding of the costs of roadway traffic congestion and the attempts to quantify these costs, an overview of the fundamental issues of interest in roadway traffic congestion are presented ranging from its definitions, causes, impacts and measures.

The impacts of congestion indicate that its price is quite high: (1) delay and unreliability in travel time, (2) inefficiency in vehicle operations, (3) reduction in levels of comfort and convenience, (4) reduced safety, (5) increases in automobile insurance premiums, (6) health impairment, (7) business-specific effects having repercussions on economic growth, (8) inefficiency in operation of transportation system, and (9) environmental damage.

Numerous alternative ways to measure congestion are then discussed. While none of these measures is universally accepted, alternative measures are valuable since they reflect various facets of the congestion problem. Examples of such measures include the following: (1) average travel speed, (2) traffic density, (3) volume-to-capacity ratio, and (4) travel time delay.

Major endeavors at quantifying the costs of congestion are discussed consisting of a summary and review of each work, focusing on data sources, major assumptions, methodological approach used for the analysis, and results. Such research efforts consist of work by the Federal Highway Administration (FHWA), the Texas Transportation Institute (TTI), the Southern California Association of Governments (SCAG), and the California Department of Transportation (Caltrans) .

Finally a comparative analysis of the results of these major research efforts is made including a discussion of the extent of quantification, and a resolution of the conflicts among their published results.

## **4.2 Conclusions**

Among the major research efforts investigated, travel delay, vehicle operations, and automobile insurance premiums are the congestion impacts for which costs were quantified. Travel delay consists of recurring and non-recurring delay. Vehicle operations' costs include fuel, oil, tires, maintenance, and depreciation. Moreover, recurring travel delay is the sole congestion impact considered by all studies. Other congestion impacts were not quantified because of difficulty in developing a methodological approach or obtaining data. The FHWA, TTI, and SCAG studies considered delay as well as at least one other impact of congestion and assigned a dollar value to the costs. Delay played a significant part for each of these quantification efforts.

Given the same geographical region (at least in name), facility type, and impact to be quantified, the analysis of differences among the results of the FHWA, TTI, SCAG, and Caltrans' studies accounted for nearly all conflicts among published estimates. Among such reasons explaining the conflicts are different (1) thresholds for the start of congestion, (2) times of the day for which congestion was quantified, (3) years for which congestion was quantified, (4) computational processes for estimating delay, and (5) freeway mileage within the region. For the Los Angeles region, conflicts among published estimates were not entirely or satisfactorily resolved.

Non-recurring delay is considered by all studies except SCAG. The assumption of equal contribution to total delay from recurring and non-recurring components is not validated by the results of the comparative analysis and requires further study.

## **4.3 Recommendations For Future Work**

Based on the results of this report, recommendations may be given to assist in providing a complete foundation of the costs of traffic congestion so that the impacts of implementing IVHS technologies may be better ascertained.

A more unified approach for congestion measurement needs to be taken to improve its estimation. This work, in fact, is ongoing at the Texas Transportation Institute, interim

findings (Phase I) have been published (Texas Transportation Institute, 1992), and Phase II work, consisting of reviewing, revising, and agency testing of the congestion measurement techniques developed in Phase I is continuing.

Measures of congestion described in this report refer to the direct roadway impact of congestion, whether it be described in terms of excess travel time, decreased speed, increased volume-to-capacity ratio, vehicle miles of travel, traffic density, or others. Research needs to be initiated to develop techniques to quantify the impacts of congestion that until now have only been considered qualitatively, e.g. degree of comfort and convenience, health impairments, reduced safety, and constraints on economic growth as a consequence of effects of congestion on businesses. Another important impact of congestion, namely, the costs of congestion-induced air pollution, also needs to be thoroughly quantified. While the costs of air pollution have been quantified (Assembly Office of Research, 1989), additional research is required to disaggregate the results into constituent parts, in particular, to determine the costs of congested-induced on-road mobile source emissions. Moreover, quantifying congestion-induced on-road mobile source emissions is currently undergoing changes in data collection and modeling techniques to more accurately reflect the actual emissions inventory (Sperling et al. 1992).

As previously indicated, additional research is required to develop a methodology to quantify non-recurring congestion. While research is ongoing (Epps et al. 1993), this approach concentrates on freeways and possibly consideration should be given to non-recurring congestion-induced delay on arterials .

Once a thorough and accurate assessment of the baseline state of the congestion problem is performed, it would then be possible, with the appropriate analytical tools, to evaluate the congestion-relieving benefits, with reliability and validity, attributable to the specific IVHS technologies under investigation. Examples of such benefits include (1) reduction in travel time delay, both recurring and non-recurring, (2) reduction in travel time variability, (3) decrease in queue lengths, (4) increase in average speeds on a network, regional, and corridor basis, and (5) reduction in the duration of incidents.

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