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MEASURING RECURRENT AND NON-RECURRENT TRAFFIC CONGESTION

Alexander Skabardonis*
Institute of Transportation Studies
University of California, Berkeley CA 94720-1720
Tel: (510) 642-9166, Fax: (510) 642-1246
skabardonis@ce.berkeley.edu

Pravin P. Varaiya
Department of Electrical Engineering and Computer Science
University of California, Berkeley CA 94720
Tel: (510) 642-5270, Fax: (510) 642-6330
varaiya@eecs.berkeley.edu

Karl F. Petty
Berkeley Transportation Systems Inc
University of California, Berkeley CA 94720-1720
Tel: (925) 253-1123 Fax: (510) 642-1246
pettyk@eecs.berkeley.edu

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ABSTRACT

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1. INTRODUCTION

Freeway congestion delay consists of recurrent delay plus the *additional* (*non-recurrent*) delay caused by accidents, breakdowns, and other random events, such as inclement weather and debris. Recurrent delay arises from fluctuations in demand, the manner in which the freeway is operated, as well as the physical layout of the freeway. Non-recurrent delay depends on the nature of the incident: an accident is likely to cause more delay than a vehicle stopped on the shoulder of the highway.

Currently, there are several approaches for defining and measuring congestion delay. For example, the California DoT (Caltrans) defines the total delay in a freeway section as the additional vehicle-hours traveled driving below a reference speed (e.g., 35 mph). Recurrent delay is measured using probe vehicles to record travel times during incident-free periods. Non-recurrent congestion is usually assumed to be equal to the recurrent congestion. Other congestion-related performance measures include travel rate, percent facility segments with demand higher than capacity, or threshold speeds. In general, however, there is a lack of consistent definition and measurement of the congestion and its components using real-world data.

The objective of the research described in this paper is to develop a methodology to identify and measure recurrent and non-recurrent congestion on freeways.

The proposed approach is applicable to urban freeways that are instrumented with loop detectors or other surveillance systems. A methodology for rural freeway facilities is presented elsewhere (1).

Section 2 presents the methodology. Its application to two real-life corridors is described in Section 3. The final section summarizes the study findings and outlines ongoing and future research.

2. PROPOSED CONGESTION MEASUREMENT METHODOLOGY

This section presents the statistical model and empirical procedures used to estimate recurrent and non-recurrent congestion on freeways, based on readily available loop detector data, such as the California's freeway performance measurement system (PeMS) (2,3).

PeMS stores and processes 2 GB/day of 30-second loop detector data in real time from most urban freeways in California. Also, incident information from the California Highway Patrol (CHP/CAD) system is stored in the PeMS database.

The basic quantity of interest is the random delay due to congestion in a highway section s over a time period t. Denote this random delay over a section-duration pair (s, t) by $D(s, t)$. $D(s, t)$ is measured in the PeMS system as the excess vehicle-hours traveled below a reference speed. More precisely:

$$D(s,t) = \sum_{\{\sigma \in s, \tau \in t\}} \max\{VHT(\sigma,\tau) - \frac{VMT(\sigma,\tau)}{V_r}, 0\}. \quad (1)$$

Here σ indexes a PeMS segment (i.e. a section of highway half-way between two consecutive detector stations), τ indexes a 5-minute PeMS average quantity, $\{\sigma \in s, \tau \in t\}$ is the set of 5-minute segment-intervals belonging to the (s, t) pair, $VMT(\sigma,\tau)$ is the vehicle-miles traveled and $VHT(\sigma,\tau)$ is the vehicle-hours traveled over the segment-interval (σ,τ), and V_r is the reference speed—either 35 mph or 60 mph.[1]

Formula (1) says that $D(s, t)$ is the excess vehicle-hours spent by vehicles over the section-duration pair (s, t) traveling at a speed below V_r mph. Observe the effect of temporal and spatial granularity in the PeMS data: aggregating over larger segments or averaging over longer time intervals (say, 15-minute) will lead to *lower* measured delays.

By accepting that the delay is a random quantity, we are also accepting that a single sample measurement of the delay—as is commonly done by measuring the delay experienced by a single probe vehicle run—does not provide a meaningful estimate of this delay. For one example segment (considered below) over the 33 days during February-April, 2002, for which there were no incidents during the morning peak period 06:00-10:00 am, the delay ranged from a minimum of 0 veh-hrs (VH) to a maximum of 1,098 VH, with a mean of 322 VH and a standard deviation of 255 VH.

Because this delay is random, our objective is to obtain a *statistical characterization* of this delay. Such a characterization may include statistical mean, variance, quartiles, and probability distributions.

We also want to separate this delay into the *recurrent delay*—the delay that occurs in the absence of incidents; and *non-recurrent delay*—the additional delay caused by incidents. Moreover, we may wish to allocate the non-recurrent delay to individual factors. Because of the limitations imposed by the CHP incident data in our empirical study, we only consider two factors: accidents and non-accident incidents.[2]

We disentangle recurrent from non-recurrent delay and estimate the impact of different kinds of incidents with the help of a statistical model:

$$P[D(s,t) = d] = \sum_{I} P[D(s,t) = d \mid I] P[I] \quad (2)$$

In this equation, $P[D(s, t) = d]$ is the probability that the random delay $D(s, t)$ equals d; I denotes the *type* of incident; $P[D(s, t) = d \mid I]$ is the probability that $D(s, t) = d$, conditioned

[1] The basic PeMS relational database tables store records of flow, occupancy, speed, VHT, and VMT. These records are indexed by detector station ID and 5-minute time interval. Another PeMS table stores incident records of location, start time, end time, and description. The congestion methodology described here can be readily applied to data available in this form.

[2] When reference is made to CHP data, 'accident' refers to any incident that involves vehicle collision.

on the occurrence of an incident of type I; and $P(I)$ is the probability of occurrence of such an incident.

In the empirical study, we distinguish between $I = 0$, $I = acc$ or accident, and $I = non$ or a 'non-accident' incident.

The empirical study has two limitations. First, in studying the delay over a particular (s, t) pair, we include only those incidents that occur within the (s, t) pair. This can cause two kinds of errors. The first limitation might be called the 'boundary effect'. Suppose an incident occurs within a section-period pair (s, t). In our study, we estimate the impact of this incident in terms of $D(s, t)$. But the incident's impact could extend to a section s' downstream of s or to a period t' after t. (In both cases, the impact would be counted as 'recurrent' congestion.) However, our empirical study does not attribute this delay to the incident that occurred in (s, t). Thus we must be careful in choosing the size of the sections and the durations to be large enough so that this boundary effect is relatively small. In our empirical study this 'boundary effect' is minimized because s is taken to be long sections (several miles) of freeway and t is a long duration—the peak travel time.

The second limitation is due to coverage. We limit ourselves to incidents reported in the CHP/CAD database. We know that this does not include all incidents. However, the accidents in the CAD appear to match well the accidents reported by the freeway service patrols (FSP). Table 1 shows a comparison between the two data sources for the I-210 test section in Los Angeles. The most underreported incident is in the 'breakdowns' category. Also, from the analysis of incident data on I-10 and I-880, for which we have detailed incident data from observers in probe vehicles, we find that CHP/CAD data includes only 15-20 percent of all incidents, but it *does* include virtually all accidents and all the delay-causing incidents (4). Other causes of non-recurrent congestion include lane closures, events, and inclement weather. In principle, these could be included in (2), simply by considering them as new kinds of incident. In the application of the methodology, we ignore these causes because of lack of data.

We can use (2) to decompose the expected value of the total delay, E[D(s, t)], into recurrent and non-recurrent delay:

$$
\begin{aligned}
E[D(s,t)] &= \sum_d d \times P[D(s,t) = d] \\
&= \sum_I \sum_d d \times P[D(s,t) = d \mid I] P[I \mid s,t] \\
&= \sum_I E[D(s,t) \mid I] P[I \mid s,t] \\
&= E[D(s,t) \mid I = 0] P[I = 0 \mid s,t] + \sum_{I \neq 0} E[D(s,t) \mid I] P[I \mid s,t] \\
&= E[D(s,t) \mid I = 0] + \sum_{I \neq 0} \{E[D(s,t) \mid I] - E[D(s,t) \mid I = 0]\} P[I \mid s,t] \\
&= \text{Recurrent congestion} + \text{Nonrecurrent congestion}
\end{aligned}
\tag{3}
$$

In the second-last equation we have used the assumption that

$$P[I=0\,|\,s,t) = 1 - \sum_{I\neq 0} P[I\,|\,s,t].$$

For our empirical analysis, this means that if there is no CHP website report of an incident during the segment-duration pair (s,t), then there is in fact no incident.

Thus, the basic relations that we will estimate are:

$$\begin{aligned} \text{Total congestion} &= \text{Recurrent congestion} + \text{Nonrecurrent congestion} \\ \text{Recurrent congestion} &= E[D(s,t)\,|\,I=0] \\ \text{Nonrecurrent congestion} &= \sum_{I\neq 0}\{E[D(s,t)\,|\,I] - E[D(s,t)\,|\,I=0]\}P[I\,|\,s,t] \end{aligned} \tag{4}$$

In addition to these statistical averages, we also wish to estimate the distributions

$$P[D(s,t)=d\,|\,I] \tag{5}$$

As mentioned, in our empirical study, we only distinguish between non-incidents (I=0), non-accident incidents (I=*non*) and accidents (I=*acc*) and so the relation for non-recurrent congestion simplifies to

$$\begin{aligned} \text{Nonrecurrent congestion} &= \{E[D(s,t)\,|\,I=acc] - E[D(s,t)\,|\,I=0]\}P[I=acc] \\ &\quad + \{E[D(s,t)\,|\,I=non] - E[D(s,t)\,|\,I=0]\}P[I=non] \\ &= \text{Congestion from accidents} + \text{Congestion from non - acc} \end{aligned} \tag{6}$$

Note in both (4) and (6), to evaluate non-recurrent congestion we have to deduct $E[D(s,t)\,|\,I=0]$ because, by definition, non-recurrent congestion is the *excess* over recurrent congestion caused by incidents. Equations (4), (5), and (6) form the basis of our empirical study.

3. APPLICATION OF THE METHODOLOGY

This section presents the application of the methodology to two real-life freeway corridors. We explain the procedures we use in the empirical estimates of the quantities in (4)-(6), and the additional assumption underlying these procedures.

<u>I-210</u>: an 11-mile section of freeway 210 in Los Angeles. The study area is between postmiles 32 and 43. Congestion delays were calculated for the AM peak period 6:00 to 10:00 AM for the period February to April 2002 (60 weekdays). Data on traffic conditions and incidents are provided by the PeMS system. The study section experiences heavy recurrent congestion in the WB direction in the AM peak.

I-880: This is a 6-mile freeway section located in the city of Hayward, Alameda County. Data on traffic volumes and incidents were provided by the I-880 FSP database (5). Two datasets were used. The 'before' data set includes information for 20 weekdays for the AM and pm peak periods. The 'after' data set includes data for 24 weekdays for the AM and pm peak periods. 'Before' and 'after' refer to periods before and after initiation of Freeway Service Patrol service.

The statistical assumption is that of *stationarity* and *independence*. More precisely, we fix a section-duration pair (s, t) in which s denotes a particular section (e.g. I-210W between postmiles 32 and 43 in LA) and t stands for a fixed weekday period such as the AM peak, 06:00-10:00. Suppose we have measurements of congestion delay and incidents for N weekdays, $t_1, \cdots, t_N$. We assume that these N samples are independent and identically distributed. With this assumption, we can use empirical averages and frequency counts to estimate the statistical averages and probability distributions in (4)-(6).

We partition the N samples into three classes: N_0 is the set of samples n for which CHP reports no incidents; N_{acc} is the set of samples for which CHP reports at least one accident; and N_{non} is the set of samples for which CHP reports at least one incident but no accident. We ignore the distinction between the occurrence of one incident and two or more incidents, because there are very few cases of the latter in the CHP website during a single AM peak duration. The distributions (5) are estimated by the frequencies:

$$\hat{P}[D(s,t) \in Bin(d) \mid i] = \frac{\text{Number of samples in } N_{\mathrm{I}} \text{ with delay in } Bin(d)}{\text{Number of samples in } N_{\mathrm{I}}}, I = 0, acc, non. \quad (7)$$

Here $Bin(d)$ stands for a delay 'bin'.

The conditional means are estimated by

$$\hat{E}[D(s,t) \mid I] = \frac{\sum_{\{n \in N_I\}} D(s,t_n)}{\text{Number of samples in } N_{\mathrm{I}}}. \quad (8)$$

Above $\hat{P}$ and $\hat{E}$ are our estimates and equations (7) and (8) summarize how these estimates are calculated from the data samples $D(s,t_n)$, $n = 1, \ldots, N$.

Figure 1 shows the three distributions, $P[D(s,t)|I=0]$, $P[D(s,t)|I=non]$, $P[D(s,t)|I=acc]$ for the 11 mile study section of I-210W (from pm 32 to 43), during the 06:00-10:00 AM peak period.

Table 2 provides some descriptive statistics on congestion delay for the I-210 site. In the table, the first column is the type of I, the second column is $P(I)$, the third column is the estimate of the mean congestion delay conditioned on the incident type, σ is the standard deviation of the samples, Error is the standard error of the estimated mean, Max$D$ is the maximum value of the delay, and Count is the number of samples.

Several things are worth noticing. First, the estimate of (5) for 60 mph reference speed is

Total congestion = Recurrent congestion + Nonrecurrent congestion

$$368.75 = 322 + 46.75,$$

hence nonrecurrent congestion accounts for 46.75/368.75 or 13 percent of total congestion along the study corridor.

The nonrecurrent congestion breakdown in (9) is

Nonrecurrent congestion = Congestion from $I = acc$ + Congestion from $I = non$

$$46.75 = 13.25 + 33.50,$$

hence accidents account for 33.5/46.75 or 72 percent of nonrecurrent congestion.

Second, as is clear from Figure 1, as well as from the large standard deviation, the probability distribution of congestion delay has a large 'tail'. Consequently, measures of congestion must account for this variation. Giving a single number to summarize congestion is very misleading.

Table 2 also shows the delay descriptive statistics for a reference speed of 35 mph, instead of 60 mph. This alters the quantitative conclusions above in two ways. The estimate of delay in each row of the table obviously goes down. Furthermore, the recurrent delay estimate (I = 0) will decline by a greater percentage, so that the percentage contribution of nonrecurrent congestion to total congestion will increase. From Table 2B we can see that the reference speed of 35 mph, non-recurrent congestion accounts for 36.58/214.41 or 17 percent of total congestion (vs. 12 percent for the 60 mph reference).

Table 3 shows the results from the application on the I-880 test site for both the before and after data sets. The results show that the percent of non-recurring congestion is about 28 to 30% of the total congestion. The same results were obtained when minor incidents (shoulder breakdowns lasting less than 10 minutes on the average) are excluded from the database. This indicates that the incident normally reported in the CHP/CAD account for most of the congestion delay.

Impacts on Travel Times

Freeway congestion increases the average and variability of travel times. Figure 2 shows the variability of travel times along the I-210 study corridor. Figure 3 shows the travel time distributions by departure time. The average travel time under free-flow conditions is 13 minutes and increases to 23 minutes under congested conditions. More importantly, the 90th percentile travel time increases by 15 minutes from 18 to 33 minutes (Figure 3).

Figure 4 shows the travel time distributions for incident and non-incident conditions for the entire peak period. The average travel time under incident conditions increases by 3.5 minutes, and the 90th percentile travel time increases by about 8 minutes.

DISCUSSION

A methodology for measuring freeway congestion and its components (recurrent vs. non-recurrent) has been developed for urban freeways that have surveillance systems. The major findings to date can be summarized as follows:

a) Freeway congestion delay is highly variable. Congestion estimates relying on a single typical day of data collection using instrumented vehicles produce misleading results.

b) Non-recurrent congestion delay is found to be between 13 to 30 percent of the total delay, which is lower than commonly quoted values of 40 to 60 % of total delay. The portion of non-recurrent congestion delay depends on the study section characteristics, frequency and type of incidents, and the presence of recurrent congestion. Most importantly, the percentage of non-recurrent delay depends on the extent of *recurrent* delay. Clearly, if there is no recurrent delay, non-recurrent delay will account for 100 % of total delay. The applications considered here deal with peak periods in freeways with significant recurrent congestion.

c) The methodology can be used to derive estimates of average travel times and travel time variability and propose travel time reliability measures.

Ongoing and future work on the subject include application of the methodology on other test sections using the extensive PeMS database, validation of the methodology with sites with available detailed data (e.g., I-10 in Los Angeles (6)), development and application of a methodology for estimating congestion on other state highways (rural freeways and multilane highways). It is also envisioned that the methodology once tested and validated will be incorporated into the PeMS system for routine use by researchers and practitioners.

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The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of or policy of the California Department of Transportation. This paper does not constitute a standard, specification or regulation.

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Figure 4. Travel Time Distributions I-210 WB--Incidents vs. Non-Incidents

Table 1. Comparison of Incident Data Sources

A. Number of Peak period Incidents/Month I-210—source FSP records

Incident Type	In-Lane	Shoulder	Total
Accident	16	42	58
Breakdown	67	532	599
Debris	27	17	44
Total	110	591	701

B. Number of Incidents I-210 Peak Periods--April 2002 source CHP/CAD

Incident Type	In-Lane	Shoulder	Total
Accident	NR	NR	54
Breakdown	NR	NR	6
Debris	NR	NR	67
Total			127

NR: not reported/incomplete information

TABLE 2. SUMMARY STATISTICS—CONGESTION DELAY I-210

A. Reference Speed = 60 mph

I	*P(I)*	*E{D/I}*	*σ*	*Error*	*Max D*	*Count*
Total	1.00	368.75	290.67	18.53	1457.75	246
I =0	0.66	322.00	255.00	19.97	1098.50	163
I = inc	0.34	460.56	384.50	42.20	1457.75	83
I = non	*0.15*	*410.58*	*304.67*	*50.09*	*1271.00*	*37*
I = acc	*0.19*	*500.75*	*352.75*	*52.01*	*1457.75*	*46*

B. Reference Speed = 35 mph.

I	*P(I)*	*E{D/I}*	*σ*	*Error*	*Max D*	*Count*
Total	1.00	214.42	196.50	12.53	1104.25	246
I =0	0.66	177.83	166.42	13.03	806.17	163
I = inc	0.34	286.19	234.20	25.71	1104.25	83
I = non	*0.15*	*251.92*	*205.17*	*33.73*	*842.83*	*37*
I = acc	*0.19*	*313.75*	*246.58*	*36.36*	*1104.25*	*46*

TABLE 3. SUMMARY STATISTICS—CONGESTION DELAY I-880
(Reference Speed = 60 mph)
A. Before

I	*P(I)*	*E{D/I}*	*σ*	*Error*	*Max D*	*Count*
Total	1.00	40.45	46.04	2.71	286.30	288
I =0	0.22	28.30	28.07	3.54	167.30	63
I = inc	0.78	43.85	49.44	3.30	286.30	225
I = non	*0.63*	*35.91*	*45.17*	*3.35*	*286.30*	*182*
I = acc	*0.15*	*77.47*	*53.05*	*8.09*	*207.61*	*43*

B. After

I	*P(I)*	*E{D/I}*	*σ*	*Error*	*Max D*	*Count*
Total	1.00	47.94	49.86	2.91	244.31	293
I =0	0.29	30.86	31.77	3.43	123.91	86
I = inc	0.71	49.91	49.14	3.42	244.31	207
I = non	*0.57*	*43.82*	*47.49*	*3.69*	*240.10*	*166*
I = acc	*0.14*	*74.51*	*48.57*	*7.59*	*244.31*	*41*

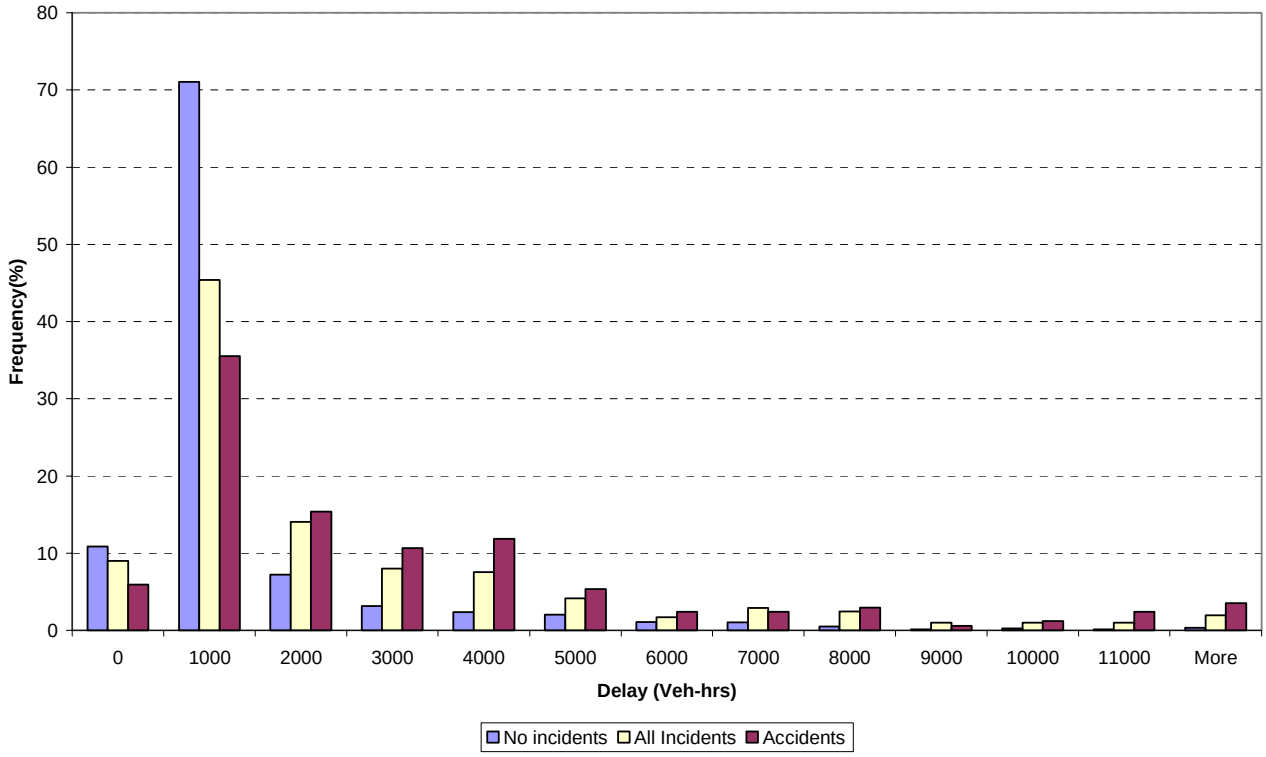

Figure 1. Delay Distribution I-210

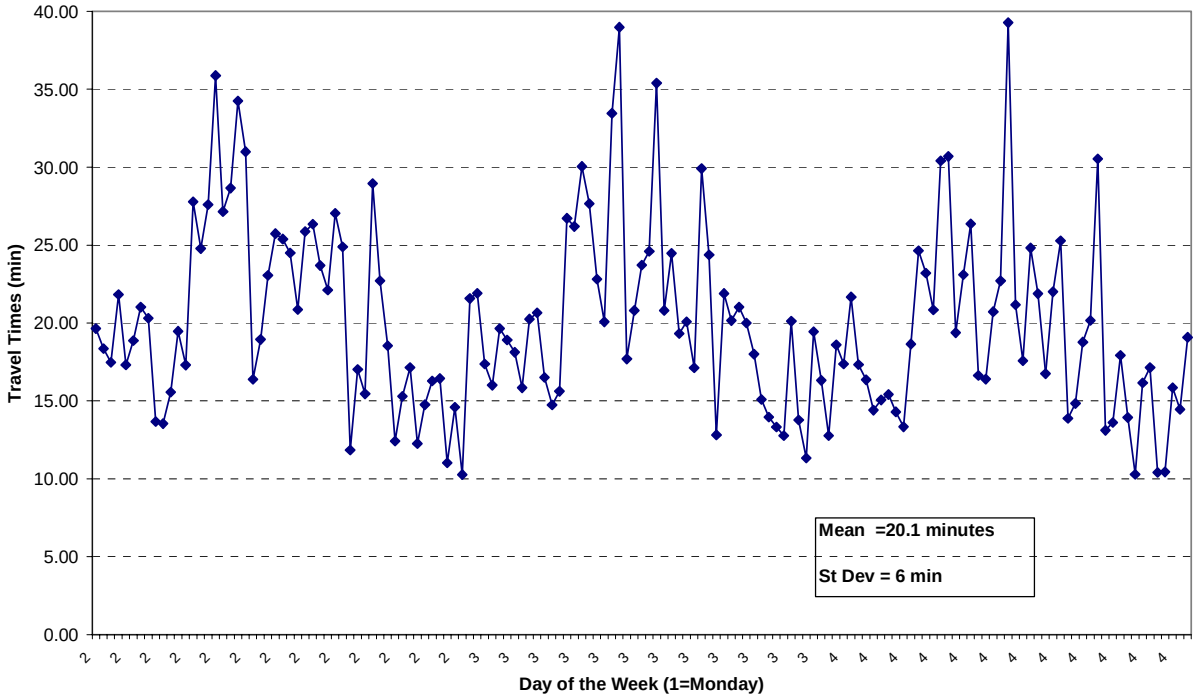

Figure 2. Travel Time Variability I-210 WB

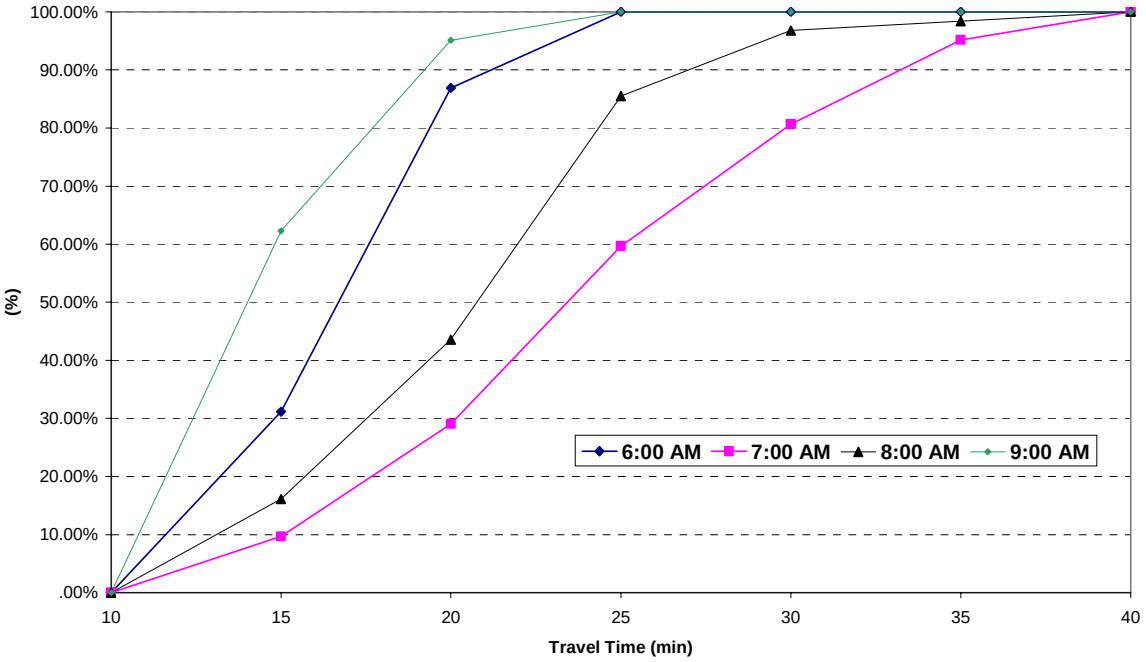

Figure 3. Travel Time Distributions I-210 WB

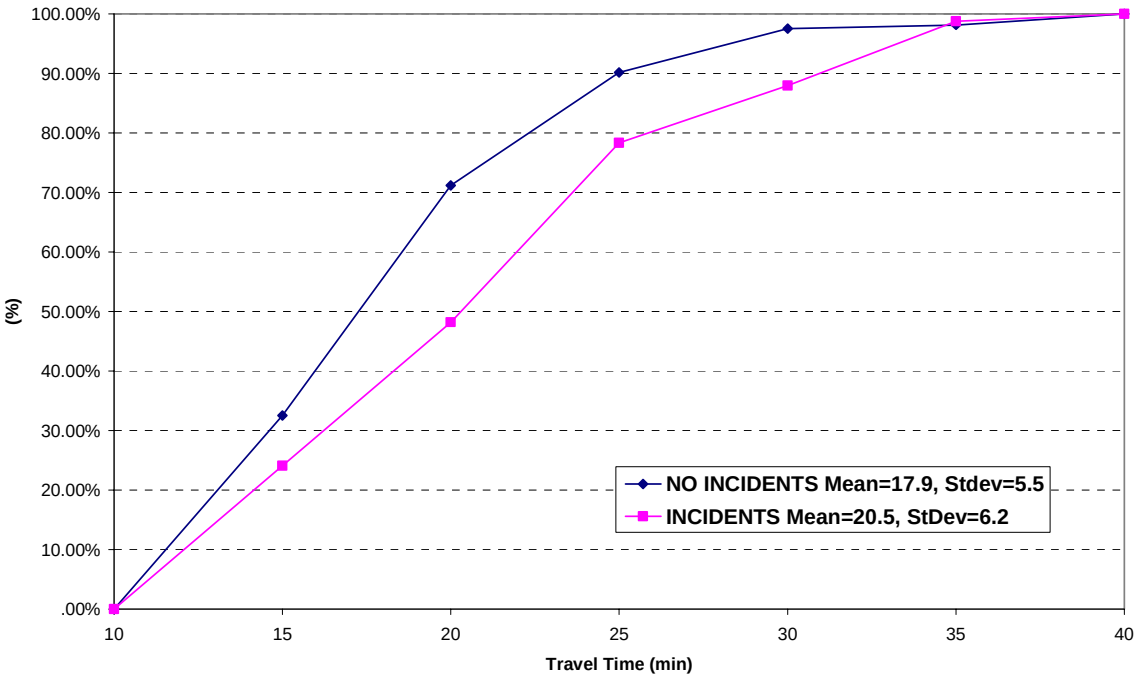

Figure 4. Travel Time Distribution I-210 WB--Incidents vs. Non-Incidents