Travel Time Reliability as a Measure of Service

Chao Chen, Erik van Zwet, Pravin Varaiya, Alex Skabardonis

INTRODUCTION

The Highway Capacity Manual defines 6 levels of service (LOS) on a scale of A through F. They are based on the density of vehicles on a freeway segment. The LOS has these three stated purposes: operational analysis, design, and planning. It is a tool for the engineer. As an indication of the service quality provided to the driver, however, it is not intuitive. The driver cares about getting from an origin to a destination in the least time. On the other hand, travel time is a direct measurement on how well the freeway is performing its function. It is also more intuitive to understand than the grades A-F. For example, to say "the travel time on I-5 South between LA and Irvine is under 60 minutes on weekdays between 7 and 8am" is much more meaningful to the driver than to say "65% of I-5 South between LA and Irvine operates at level D or below" during those times.

Travel time is not used as a measure of service quality partly because the data are hard to obtain. However, this is about to change. In California, all the major urban freeways are instrumented with loop detectors. PeMS (Performance Measurement System, http://transacct.eecs.berkeley.edu) is a data collection and analysis system that calculates travel time and stores historical travel times on-line. We present travel time statistics for a corridor in the Los Angeles area. We also show the effects of incidents on travel time and its variability. We show that quantile travel times are very useful measures of freeway service quality. Loop detectors are installed on freeways in most US metropolitan areas, so the methods described here can be used to calculate travel time statistics in these areas. While the average travel time is indicative of service quality, the variability in travel time is also important. We propose using the standard deviation and the 90th percentile travel time, in addition to the mean, to measure service quality. The standard deviation is a well-accepted measure of variability, and the 90th percentile measures the extremes.

Traditional measures of LOS also indicate the service quality. In fact, LOS and travel time contain much of the same information about the underlying traffic. Of these two, travel time provides more specific and intuitive information to the driver, while LOS is a more detailed measurement that can be used to diagnose problems. Thus, LOS is a detailed diagnostics tool that is more useful for the engineer, while travel time is more meaningful as the ultimate success or failure of the freeway operator. Of course, they are highly correlated quantities. Conceptually, the travel time of a route is a summary of the LOS of the segments that make up that route.

TRAVEL TIME VARIABILITY IN LOS ANGELES

Travel time is a natural measure of effectiveness of a freeway. The purpose of freeways is to transport people to where they want to go. The measure that is the most important to people is the travel time. While safety, simplicity of the route, and scenery play some role, they are of less concern to most people.

If I drive on the same route at the same time each day for many days, experience tells me that I can expect a wide range of travel times. Data also show that travel time is highly variable during peak hours. On a 20-mile route on I-5N in Los Angeles, California, for example, the afternoon peak hour can see travel times anywhere between 30 and 50 minutes. Therefore to fully describe travel time on a route for a certain time of day, one needs to specify the distribution of travel times, rather than simply the average. The importance of the distribution is clear in the following example. Suppose I need to arrive at the airport at 5pm in order to make a flight, and I want to decide the latest time I can leave my house and still have a high probability of arriving on time. The average travel time is not useful here, nor is the median. What I really need to know is the 90th percentile travel time. Suppose this is 57 minutes. This tells me if I always left my house at 4:03pm to catch the 5pm flight, then I will miss the plane only one out of ten times. Although we don't think about our decisions this way, this is what's going on when we decide how much time to budget, though people may use different thresholds than 90%.

The average travel time is also important. Suppose I have two ways of getting home from school, one by train and is the other by car. If I take the train, my travel time is always 50 minutes; if I drive, 11% of the time someone has an accident and my travel time is 60 minutes, and 89% of the time it's 30 minutes, so the average is about 33 minutes (0.11*60 + 0.89*30 = 33), but the 90th percentile is 60 minutes. I always get out of school at 6pm, and I'm only interested in maximizing the time I spend at home with my kids before I go to bed. Therefore I only care about the average travel time, and I would drive everyday. These examples show that both the average and the 90th percentile travel time need to be included in the performance measure of a freeway route.

Calculation of Travel Times from Measured Speeds

Travel times are computed from the measured speeds in time and location, $v(t_i, x_j)$ (*1*). Starting from a time τ_0 and location y_0, we find a trajectory $y(\tau)$ whose speed $y'(\tau)$ obeys the measured speeds $\hat{v}(\tau, y)$. This is expressed as

$$\frac{dy}{d\tau} = \hat{v}(\tau, y)$$

EQUATION 1

We compute the trajectory from measured speeds at discrete times and locations (t, x) where $t \in t_1, t_2, \ldots, t_m; x \in x_1, x_2, \ldots, x_n$ for m sample times and n locations. The speed is defined for each (t_i, x_j). Starting at τ_0 and y_0, we first find the speed at that point $\hat{v}(\tau_0, y_0)$, where

$$\hat{v}(\tau, y) = v(t_i, x_j), \ \ i : |t_i - \tau| \le |t_k - \tau| \quad \forall k; \quad j : |x_j - y| \le |x_k - y| \ \forall k$$

EQUATION 2

is the approximation of speed from discrete measurements. We define an interval Δ = 0.1 minute, and grow the trajectory iteratively, as follows,

$$y_{h+1} = y_h + \Delta \hat{v}(\tau_h, y_h)$$
$$\tau_{h+1} = \tau_h + \Delta$$

EQUATION 3

until we reach the end of the segment. The computed trajectories and their underlying speed field are shown in FIGURE 1. These trajectories vividly illustrate the changing speeds experienced by a vehicle traveling under the measured conditions. The travel time of each trajectory is the difference between the starting time and the time the trajectory reaches the top of the plot.

Travel Times on I-5 Corridor

We now present the travel time statistics on a section of I-5 North in Los Angeles County. The raw data are in the form of speed versus time and location. They are provided by PeMS. The corridor in this study is 20 miles long, between postmiles 0 and 20. We computed the travel time on this corridor on 65 weekdays between 3/1/2002 and 6/1/2002, between 5am and 10pm each day. While the raw measurements are noisy, the computed travel times are very informative and easy to interpret. For example, in FIGURE 1, the speed field looks chaotic and hard to interpret. But the trajectories are clear and intuitive, because they describe the experience of a driver who navigates through the speed field.

The travel times of trajectories starting every 17 minutes are computed for each day. The median, mean, 10^{th} and 90^{th} percentile travel times are plotted in FIGURE 2 for each departure time of day. There are several things to note about this picture. First, it shows a clear trend of higher travel times during peak periods, as expected. It also shows the wide range of travel times that can be expected on any given day. Second, it quantifies general time of day trends in terms that are meaningful to the driver. For example, to be sure of arriving at the destination at 6pm (with 90% probability), one must leave 55 minutes earlier; to arrive at noon, one only needs to budget 40 minutes.

Standard Deviation and Percentile

The standard deviation is a commonly used statistic to describe the variability of a random variable. The standard deviations of travel times for each departure time of day are plotted in FIGURE 3; FIGURE 4 shows the relationship between σ and μ. They are highly correlated (correlation coefficient = 0.85), and standard deviation increases with mean travel time, as we expect. In the literature, the standard deviation, along with mean travel time, is frequently used to calculate the cost of driving in a corridor (*2*,*3*).

$$c = r_1\mu + r_2\sigma$$

EQUATION 4

where

- c = cost
- μ = mean travel time
- σ = standard deviation of travel time
- r_1 = cost per unit time of average travel time
- r_2 = cost per unit time of standard deviation

This formulation uses two rates for the cost of time, and the second rate, r_2, doesn't have a physical interpretation. We suggest an alternate way of pricing congestion, using the 90^{th} percentile travel time. In this model, the cost of travel is the time one must budget to be reasonably assured of on-time arrival, with probability *p*. If p=0.9, then the actual cost of a trip is the 90^{th} percentile travel time multiplied by some rate:

$$c_p = r_1 t_{0.9}$$

EQUATION 5

where *T* is the travel time, a random variable, and t_α is such that $P(T < t_\alpha) = \alpha$. This formulation of cost has a more intuitive interpretation than the one using standard deviation. Studies show that both average travel time and its variability are important to drivers. The 90^{th} percentile travel time is a meaningful way of combining the effect of both into one number.

While the percentile travel times are more useful in making scheduling decisions, the standard deviation is important in that it isolates the variability from the mean. Also, it is well-defined, whereas the percentile requires specifying which percentile (80^{th}, 90^{th}, 95^{th}, etc). Therefore we recommend using both the standard deviation and the 90^{th} percentile as performance measures of corridors.

The Impact of Incidents

Experience tells us that incidents can cause large delays. We show that using the data available today, we can quantify the impact of accidents on travel time. We gathered incident information from the California Highway Patrol (CHP) website. An incident can be any number of events, such as vehicle collision, stalled vehicle, debris on road, etc. Each incident has a start and an end time, a classification, and a location. In this study, we don't differentiate among different types of incidents and treat them all as just "incidents." In the future, we need to identify the impact of incidents in each of the CHP defined classes.

The incidents were correlated with trips, which are the trajectories calculated from measured speeds, like the trajectories in FIGURE 1. There is a trip departing every 17 minutes from the origin, on each of 65 weekdays. A trip is said to be an *incident trip* if at any time during the trip, there is an incident anywhere on the study section. For each departure time of day, there are 65 trips, one for each day. Each trip was classified as an incident trip or a non-incident trip. The fractions of incident trips are plotted by departure time in FIGURE 5. This plot shows, for example, that the trip departing at 10am has a 60% chance of witnessing an accident. Overall, it shows high rates of incidents during peak hours.

We quantified the effect of incidents on travel time. As expected, both the standard deviation and the median of travel time are larger when there are incidents, as shown in FIGURE 3 and FIGURE 6. While the presence of incidents consistently adds about 5 minutes to the median travel time of most trips, their effect on standard deviation is strongest during midday, non-peak hours. This may be because the flows during these periods are not large enough to cause congestion normally, but they are high enough that an incident can trigger a breakdown and create congestion. In contrast, in early morning or late at night, the traffic is so light that congestion doesn't form even when there are incidents.

The combined effect of increases in average and variance of travel times is captured in FIGURE 7, which shows the 90^{th} percentile travel time under incident and non incident conditions. FIGURE 7 has valuable information for the driver. For example, if one wants to arrive at an appointment at 3pm, and there are no reported incidents, it's enough to budget 35 minutes; if there is an incident reported, one must budget 50 minutes.

TRAVEL TIME AND LOS

The Highway Capacity Manual (HCM) *(4)* defines the Levels of Service (LOS) of a homogeneous road segment, which on a freeway refers to a segment with no ramps or major geometric changes. The LOS is given on a scale from A to F based on vehicle density. Its definition is in TABLE 1. As LOS can also be specified in speed or flow rates. The thresholds of speed and flow rates are the values corresponding to the density thresholds on the speed-density and flow-density fundamental diagrams.

LOS is used to determine the service quality provided to the driver. Levels E and F are considered stop-and-go traffic, and it is believed that drivers prefer to travel in lighter traffic (A-D), even if travel time is fixed. This is reasonable since higher density means more stress and chances of accidents. In most situations, travel time and LOS are highly correlated. To illustrate, we present FIGURE 8, which shows the *expected fraction of the corridor where the level of service is F*, for each time of day. This plot is produced in the following way. First, we found the LOS for each location on the corridor (there are about 30), at each time of day, for 22 days. Let $L(d,t,x)$ be this quantity. We then aggregated spatially for each sample time to find the percent of the freeway that has LOS F:

$$P_F(d,t) = \frac{1}{n_x} \sum_{x \in [a,b]} 1(L(d,t,x) = F)$$

EQUATION 6

where a,b are the boundaries of the corridor and n_x is the number of detector locations. Next, we computed the average of $P_F(d,t)$ over the set of days d –

$$R_F(t) = \frac{1}{n_d}\sum_{d=1}^{n} P_F(d,t)$$

EQUATION 7

where n_d is the number of days. This plot means, for example, that a trip made at 8am in the morning will have 30% of its length in congestion. But what does that mean to a commuter? Should he wait until 9am, when the figure becomes 20%? On the other hand, FIGURE 8 has the same trend as the travel time plot in FIGURE 2, which implies that travel time as a measure of service quality already contains much of the information as LOS. Of the two, travel time has much more practical value – it tells you what time to leave the house.

LOS is most useful as a diagnostic tool for the traffic engineer, because it gives a detailed picture of traffic quantities, whereas travel time is a kind of average LOS. For example, one may find that the travel time on is unusually high on a particular freeway. The traffic engineer's job is to improve the travel time and, to do that, he needs to know which part of the freeway is contributing more to congestion. LOS gives him a better indication, because he can look at the LOS of each segment that makes up the route and determine the worst one. Once he decides on a solution for a segment—such as widening the shoulder or cutting down a tree that is obstructing a sign—and implements it, he looks at the LOS of that segment after the fix to see if it improved.

We computed the LOS for each location on the same corridor that we used to compute travel time. FIGURE 9 shows the median density, and the corresponding LOS, at each location for three time periods. We see that the LOS deteriorates as rush hour advances. Most locations have LOS between B and D even between 5 and 6AM, and most locations have LOS of E or F between 7 and 8AM. These plots contain location-specific information that may help a traffic engineer find the cause of congestion. For example, there are two density peaks at miles 7 and 11. These could be locations of bottlenecks and deserve further attention. (The points at mile 7 are actually bad data points from a faulty detector, but the trend is the same.)

CONCLUSION

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TABLE 1 Definition of LOS from the HCM.

LOS	Density(veh/mi/ln)	Speed(mph)	Flow (% of capacity)
A	≤12	≥60	≤35
B	≤20	≥57	≤54
C	≤30	≥54	≤77
D	≤42	≥46	≤93
E	≤67	≥30	≤100
F	>67	<30	Unstable

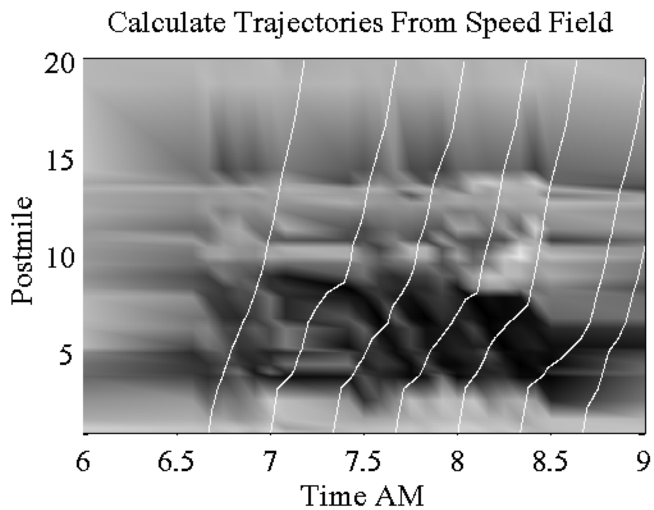

FIGURE 1 Trajectories computed from the underlying speed field. The dark regions have low speed, lighter regions have high speed. Speed has been smoothed. Vehicles travel up the page, departing from left to right.

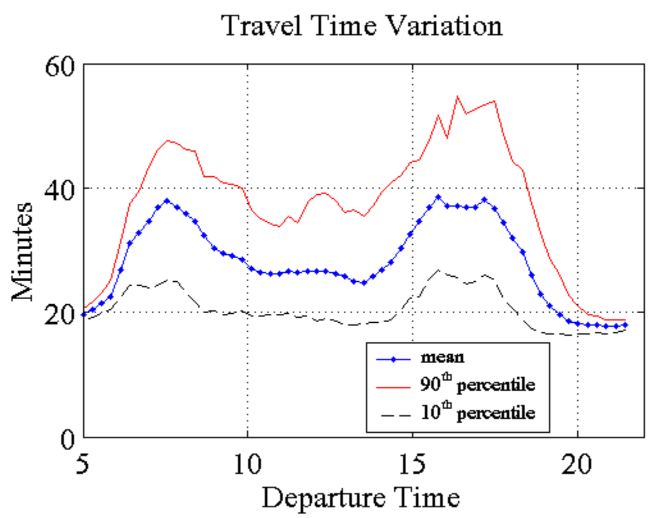

FIGURE 2 Travel time statistics on I-5 North, between postmiles 0 and 20, for 4am - 12pm. The data are collected on weekdays between March and June, 2002. This is the direction into Los Angeles.

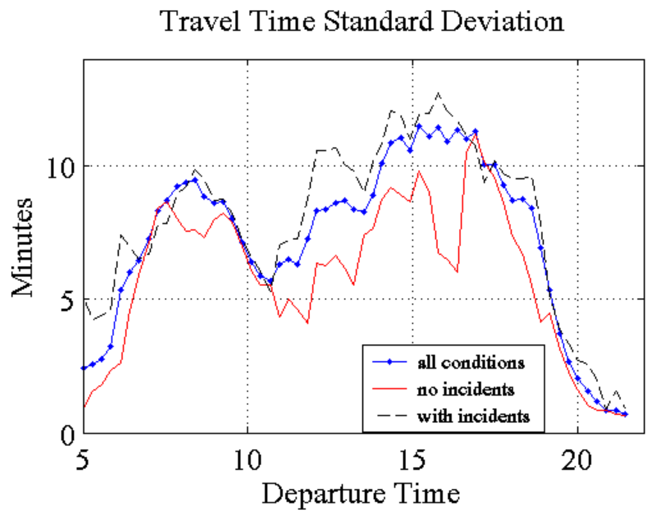

FIGURE 3 Standard deviation of travel times on 20-mile section of I-5N.

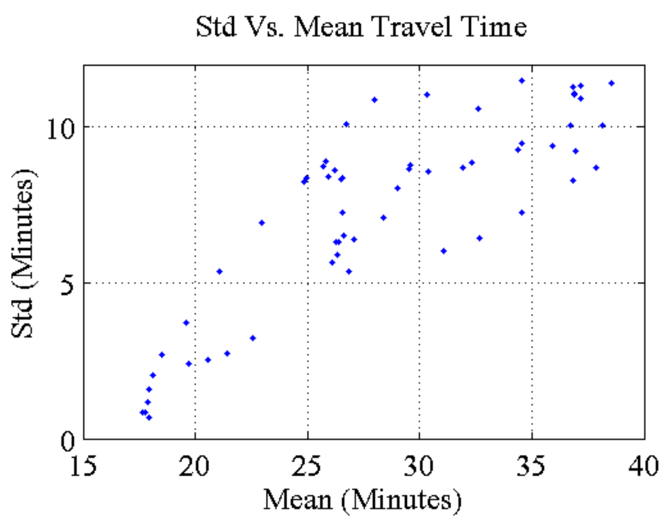

FIGURE 4 Scatter plot of σ and μ, where each point corresponds to a departure time of day.

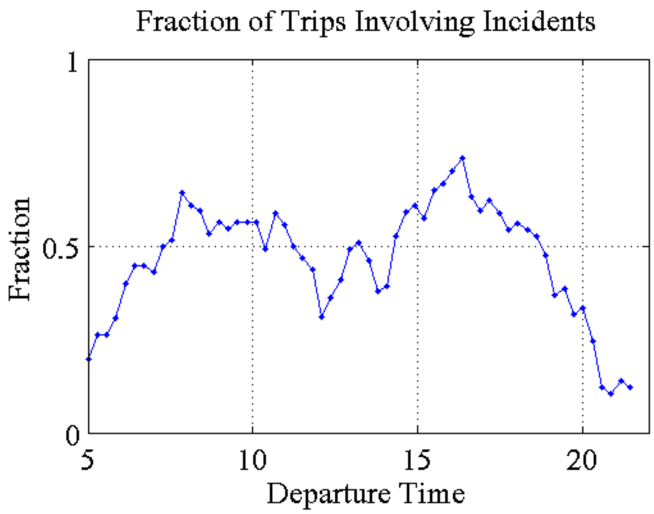

FIGURE 5 Number of trips without incidents, for each departure time. Total = 65 days.

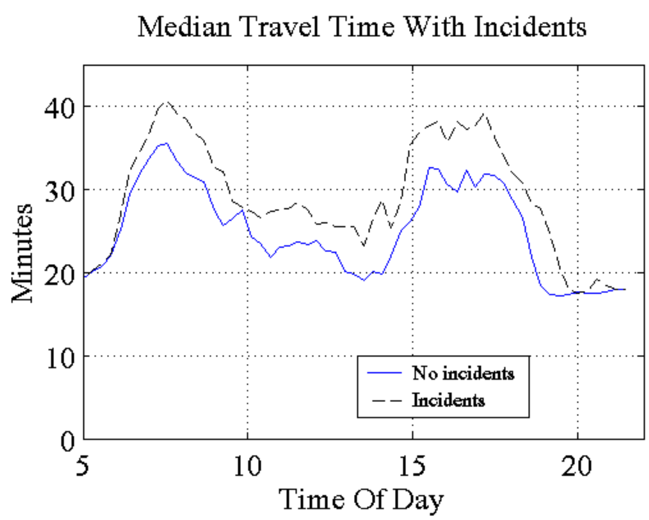

FIGURE 6 Median travel times with and without incidents.

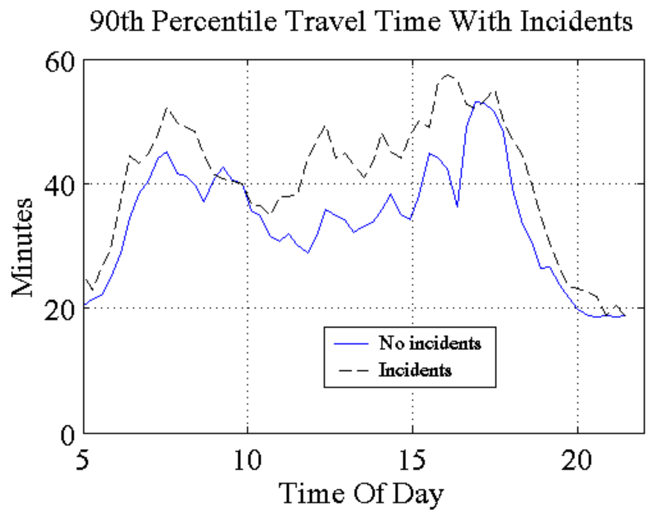

FIGURE 7 Ninetieth percentile travel time under incident and non-incident conditions.

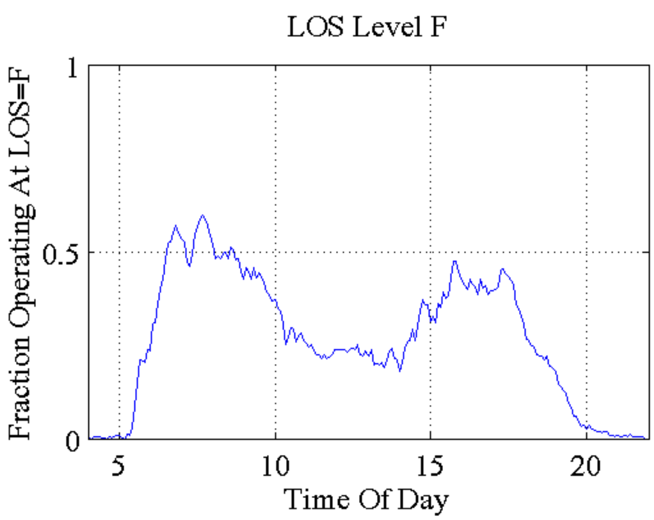

FIGURE 8 Out of 22 weekdays in May, 2002, the fraction of the corridor I-5N whose LOS is F.

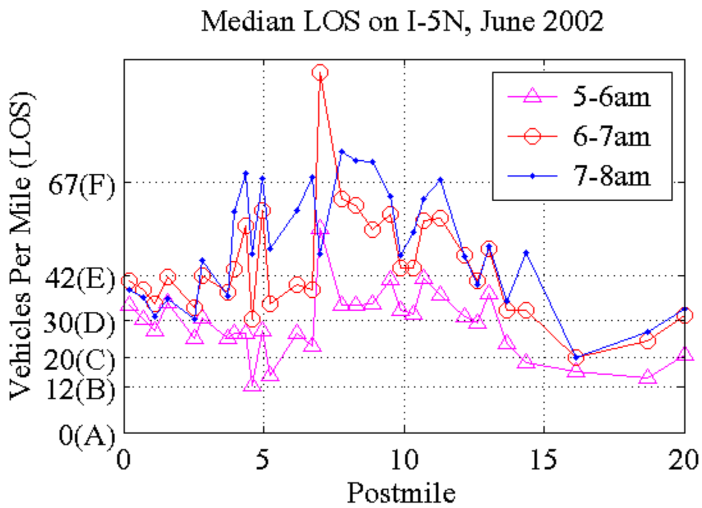

FIGURE 9 Median LOS at locations on I-5N for 3 time periods. The points at mile 7 are data from a bad detector.