TIME-VARIANT TRAVEL TIME DISTRIBUTIONS AND RELIABILITY METRICS AND THEIR UTILITY IN RELIABILITY ASSESSMENTS

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ABSTRACT

There are metrics of reliability that have been recommended. Here we investigate the variation of travel time distributions by time of day at fine temporal aggregation levels, the sensitivity of reliability metrics to these variations, the effect of the aggregation on the calculated metrics, and the amount of data required to estimate stable values of the reliability metrics.

The results show that the parameters of travel time distributions vary among periods reflecting the effects of the traffic congestion, traffic flow dynamics, and the contribution of non-recurrent factors such as incidents to the unreliability of travel time on the investigated facility.

Key Words: Travel Time Distribution, Travel Time Reliability, Performance Measurements

1 BACKGROUND

Increasingly, travel time reliability is considered as an important component of the performance of transportation systems and of travelers' perceptions of this performance. The increased recognition of the importance of travel time reliability is reflected by changes to traditional monitoring programs. For example, in a report published in July 2005, the National Operations Coalition (NTOC) initiative selected the Buffer Index (BI), a travel time reliability measure, as one of few good measures for transportation operations agencies to use for internal management, external communications, and comparative assessments (NTOC, 2005). Public agencies from around the United States are now using travel time reliability metrics as key performance measures to monitor their system operations (GRTA, 2007; GDOT, 2011; FDOT, 2008; SCAG, 2005; WSDOT, 2011; Elefteriadou and Xu., 2007; Elefteriadou *et al*, 2008). Recognizing the critical need for researching travel time reliability, the Second Strategic Highway Research Program (SHRP2, 2010) has specified travel time reliability as one of the four main research areas of the program and has funded extensive research activities in this area.

Travel time reliability measures the level of consistency of travel conditions over time. A unifying reliability definition can be found in final report of the SHRP2 LO3 project were reliability is defined as "the level of consistency in travel conditions over time and is measured by describing the distribution of travel times that occur over a substantial period of time…". The different approaches to defining reliability have lead to recommending several metrics for use. These metrics may not necessarily produce consistent assessments of reliability among themselves, since they define travel time consistency in different manners.

Tu (Tu *et al*, 2007) classified reliability metrics into: statistical range methods, buffer time methods, tardy trip measures, probabilistic measures, and skew-width methods. Lomax discussed the development of reliability measures and the factors to consider before selecting a measure (Lomax et al., 2003). They concluded that the metrics that are most promising are the Percent of Variation, Misery Index and the BI. This conclusion was based on five factors including the compatibility with multimodal analyses, ability to measure urban and rural travel conditions, consideration of the effects of trip length and time, ability to serve several audiences, and applicability to different area sizes. In a later work, van Lint and van Zulen noted that the BI and the Misery Index may not be appropriate because of the underlying skewed travel time distribution (Van Lint and van Zulen, 2005). They concluded that most of currently utilized reliability metrics should be used and interpreted with some reservations.

The common assumption about the normality in travel time distribution was investigated by Rakha (Rakha *et al*, 2007). The study concluded that the normality assumption is not supported by the observed data. Instead they proposed that a log normal distribution can describe better the travel time during uncongested conditions. Similarly during the congested hours a mixed or a bimodal distribution fits better the observed travel time distribution. Additionally, they pointed out that the rate at which the mean changes during the congested hours can be faster than the rate of change of the standard deviation, thus the coefficient of variation may decrease when actually trips are becoming more unreliable.

Pu (Pu, 2010) examined analytically a number of reliability metrics assuming a lognormal distribution of travel time with a constant median, while varying the variability and skewness of the travel time distribution. He concluded that the coefficient of variation is a good proxy for a range of reliability metrics and suggested that the use of the BI is not always appropriate unless BI is computed based on the median rather than the mean. The latter is because in heavily skewed travel time distributions the use of the mean may underestimate the travel time unreliability. The same author in a different study pointed out that some reliability metrics may be inconsistent in their depictions of reliability, such as is the case of the BI that remains constant for different values of the coefficient of variation (Pu *et al*., 2010). As discussed later in this paper, fixing the median while varying the standard deviation and skewness as is done in the Pu study may not reflect real-world conditions, in which the parameters of travel time distributions vary by time of day and may be correlated with each other.

The SHRP 2 LO3 (CS et al, 2010) project examined a set of six reliability metrics to determine their sensitivities to different types of freeway improvements. The utilized metrics were the BI, On-Time Performance, 95^{th} Planning Time Index, 80^{th} Percentile Planning Time Index, Skew Statistic and Misery Index. Based on empirical tests, it was found that all metrics were sensitive to the effects of improvements. However, it was noticed that the 95th percentile travel time or TTI may be too extreme a value to be influenced significantly by operations strategies and that the 80th percentile was more sensitive to these improvements. Another aspect, related to the amount of data required to assess systems reliability was tested concluding that an absolute minimum of six months of data is required to establish reliability within a small error rate, in areas where winter weather is not a major factor. However, a full year of data is preferred.

Even though reliability metrics have been explored and compared as discussed above, most of the work in the literature have focused on using these measures for relatively coarse levels of aggregation of travel time data, for example for the whole peak periods. Such uses imply that the parameters of the travel time distributions are assumed to remain the same for the whole period of analysis. This may not be sufficient for advanced management strategies such as for setting managed lane pricing and for capturing traveler's behaviors for use in dynamic traffic assignment (DTA)/simulation modeling. These models are normally used to simulate traveler's route selection behaviors at 15 to 30 minute intervals and are being extended to include reliability in their generalized cost functions. In addition, the analyses of the Highway Capacity Manual (HCM, 2010) are also conducted at the 15 minute analysis level and although the procedures of the current version of the manual do not consider reliability metrics, discussion has already started for the potential inclusion in future versions. This above discussion supports the argument that the reliability metrics need to be assessed at fine grained levels of aggregation for an increasing number of applications.

This study investigates the variation of the parameters of travel time distributions by time of day, the sensitivity of various reliability metrics to these variations, the effect of time of day analysis interval on the calculated metrics, and the amount of data required to estimate stable values of the reliability metrics. The investigation is made for a facility that has a general purpose (GP) lanes and high-occupancy toll (HOT) lanes, allowing the comparison of how travel time reliability attributes between the two facilities by time-of-day can be depicted by different reliability metrics. The study also explores the trends of the variations of various metrics as the congestion increases during the peak period, which is important when selecting reliability metrics for various applications such as the use of the metrics as part of the generalized cost functions of assignment models and in optimization of strategies such as congestion pricing.

2 UTILIZED TRAVEL TIME DATA

Agencies have used Intelligent Transportation Systems (ITS) devices to collect traffic parameter measurements for operational purposes. In recent years, these agencies have started archiving the collected information for future uses (FHWA, 2008). The availability of the archived information allows the analysis of travel time distributions and the associated reliability measures at a fine time scale compatible with the requirements of advanced strategies and analysis applications.

The data used in the analysis of this study was obtained from a 6.5 mile segment of the northbound direction of the I-95 limited access facility in Miami, Florida. This segment has a total of six lanes which two of these lanes are HOT lanes and the remaining four lanes operating free of charge as GP lanes. The two HOT lanes have been in operation since December 2008, utilizing a dynamic congestion pricing scheme. Registered vehicles with high occupancy can use the HOT lanes without paying tolls. The HOT lanes have a single entry point and a single exit point and are fully segregated from the GP lanes by plastic poles. This section of I-95 is equipped with point traffic detectors located every 0.3-0.5 miles that collect volume, speed and occupancy measurements every 20 seconds for both the HOT and GP lanes. The corridor operations and the data gathered by ITS devices are managed by the Florida Department of Transportation (FDOT) District 6 by means of traffic management software referred to as the SunGuide software (Southwest Research Institute, 2010).

This study utilizes travel time estimates for the HOT and GP lanes that are archived for every minute of the day by the SunGuide software. The travel time is estimated by the system based on the speed measurements collected by the microwave detectors installed on the corridor utilizing the mid-point speed estimation method. The mid-point method is a widely used travel time estimation algorithm in traffic management center software. The Mid-Point method assumes that each detector speed measurement represents the speeds of half distances to the next detector on both sides. The segment travel time is thus calculated as follows:

3 TIME-VARIANT TRAVEL TIME DISTRIBUTIONS

Travel time reliability metrics are calculated to reflect the variability of travel time from day to day. Thus, they are supposed to represent the attributes of travel time distributions that are most relevant to the perception of system reliability. Since the purpose of this paper is to examine the attributes of time-variant reliability metrics, it is useful to examine first the time variant parameters of travel time distributions of the HOT and GP lanes. In addition, as stated earlier, previous reliability studies have calculated reliability measures for the whole peak periods, implicitly assuming that the travel time distribution parameters remain constant during these periods of the analysis. Investigating the variations in travel time distribution parameters by time interval allows the examination of the validity of this implicit assumption.

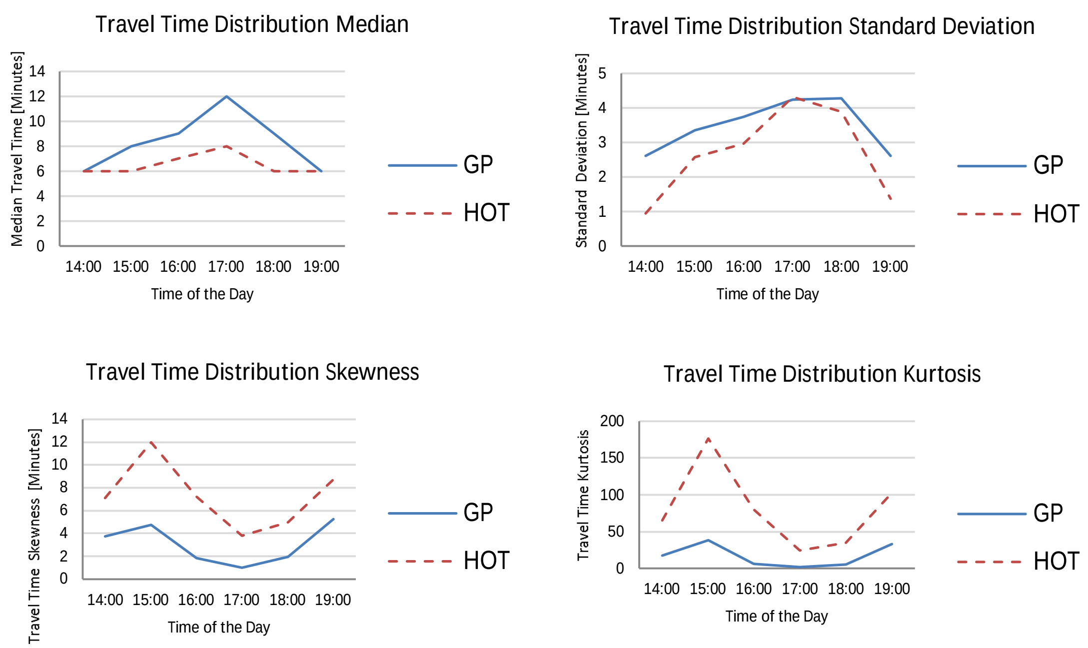
Comparing the parameters of travel time distributions for GP and HOT lanes can also provide important information regarding the sources of the unreliability of these facilities. In general, these sources can be classified as recurrent and non-recurrent events. Recurrent events include demand fluctuations, variations in traveler behaviors, and stochastic variations in flow breakdown and capacity. Non-recurrent events include incidents, work zones, special events, and weather events. Conditions with travel time variability mainly due to recurrent events are expected to have distributions that are much flatter and symmetrical compared to conditions with variability mainly due to non-recurrent events, which are expected to have skewed distributions with sharp peaks.

The compared parameters of the travel time distributions are the median, standard deviation, skewness, and kurtosis (NIST/SEMATECH, 2010). The median travel time is a measure of central tendency that is preferred to the mean in the case of skewed distributions (CS *et al*, 2010; Rakha *et al*, 2007; Pu, 2010). The standard deviation is a measure of the travel time variability and has been used as a reliability measure by itself. The coefficient of variation, which is the standard deviation divided by the mean has also been used for this purpose (Rakha *et al*., 2007) however it was not in this study as a reliability metric because it has been shown that this parameter may not represent well the travel time variation, especially when the mean/median varies. Skewness is a measure of travel time distribution asymmetry and its value can be negative or positive with positive values indicating that a longer tail of the distribution is on the right hand side of the distribution and the bulk of the travel time values lie to the left of the mean and the median. It is expected that a positively skewed travel time distribution with high skewness occurs when a high proportion of the reliability is due to non- recurrent events such as incidents, work zones, bad weather, or special events. The fourth parameter, the kurtosis, is a measure of the "peakedness" of the travel time distribution. Kurtosis combined with skewness can be used together to assess how far is the travel time distribution from the symmetrical normal distribution with the same median and standard deviation and thus how much do no recurrent events contribute to the overall unreliability of the system.

Figure 1 shows that during the congestion period between 3:00 PM and 7:00 PM, the HOT lanes always had a lower median travel time than had the GP lanes. Both facilities reached their maximum median travel time at 5:00 PM, which are 8 minutes for the HOT lanes and 12 minutes for GP lanes (the free flow travel time is about 6 minutes). Figure 1 shows that as the median travel time increases, so does the standard deviation. However, the skewness and kurtosis are higher at lower congestion levels, indicating lower correspondences between the distributions of travel time and normal distributions at low congestion levels and possibly a higher contribution of non-recurrent events to unreliability.

Figure 1 clearly indicates that the parameters of travel time distributions are highly variables as a function of time. This is even more in the case of managed lanes due to the shorter peak period that occurs only after the GP lanes start getting congested and motorists start diverting to HOT lanes due to this congestion. During most of the investigated period, the travel time variability of the HOT lanes as measured by the standard deviation is lower than that of the GP lanes, except at the peak hour (5:00 PM), when the variability of both facilities approaches each others. The higher skewness and kurtosis of the travel times of the HOT lanes indicates a higher contribution of the non-recurrent events to the unreliability on the HOT lanes. It is interesting to note that the although the variability of the travel time of the HOT lanes is lower than that of the GP lanes for most of the intervals during the investigated period, it is equal to that of the GP lanes at the peak hour (5:00 PM). This occurs in spite of the lower travel time median on the HOT lanes at the peak hour. This could be due to the higher impacts of nonrecurring events such as incidents on HOT lanes compared to GP lanes, possibly reflecting the more difficult incident site management and traveler diversion from these lanes during incident condition for de heavily congested conditions during the peak hour. This potential explanation can be further supported by the comparison of the time-variant reliability metrics in the next section.

Figure 1: Travel time distribution shape parameters



4 TIME-VARIANT RELIABILITY METRICS

As described previously, it is important to examine how the reliability metrics vary by time-of-day and particularly how do they react to the increase in demand. These metrics have to be sensitive to the increase in congestion and they need to show a consistent trend as the congestion increases in order to allow their use in highway capacity/traffic analysis applications, or when included as parameters in the objective functions of dynamic traffic assignment tools or of the optimization of the pricing of managed lanes and other strategies.

There are a number of metrics that have been used to quantify reliability. The variation in the parameters of the travel time distributions with the increase in congestion by time of the day as described in the previous section is expected to have significant impacts on the values of these metrics. In this study, an investigation was made of the sensitivity of the reliability metrics to the changes in the congestion levels and the ability of these metrics to reflect the reliability differences between the HOT and GM lanes in a time-variant context. Table 1 shows the definitions of travel time reliability measures used in this study. These measures are mainly selected based on the recommendations given in SHRP2 L03 project (CS *et al*, 2010) and constitute a common set of metrics used for reliability assessments.

Table 1: Travel Time Reliability Operational Definitions

Reliability Performance Metric	Definition
Buffer Index (BI)	The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time.
Failure/On-Time Performance	Percent of trips with travel times less than: • 1.1* median travel time • 1.25* median travel time
95th Planning Time Index	95th percentile of the travel time index distribution
80th Percentile Travel Time Index	80th percentile of the travel time index distribution
Skew Statistics	The ratio of 90th percentile travel time minus the median travel time divided by the median travel time minus the 10th travel time percentile
Misery Index	The average of the highest five percent of travel times divided by the free-flow travel time.

Source: SHRP LO3

In this study, the reliability metrics in Table 1 were estimated for the GP and HOT lanes, utilizing different time interval lengths in the analysis. The results presented in Figures 2 and 3 are based on 15 minute intervals. Figure 2 and Figure 3 show different trends of different reliability metrics with time of day for the GP and HOT lanes respectively, as explained below.

The metrics that exhibit continuity and sensitivity in their variations in response to the increase in variability as the congestion in the peak hour is approached are the 95th Percentile Planning Time Index (PTI), 80th Percentile PTI, and the Misery Index. Figures 2 and 3 show that the use of the 95th Percentile PTI metric and even more the use of the 80th percentile PTI metric clearly indicate that the reliability decreases as the peak demand period, at 5:00 PM, is approached. The reliability is lowest at this peak reflecting the highest variability observed when examining the parameters of the travel time distributions, as discussed in the previous section. Figures 2 and 3 also show that the 95% PTI of the GP lanes is higher than that of the HOT lanes except at the peak hour, at which the PTI is equal for both facilities, reflecting the comparable travel time variability of the GP and HOT lanes at the peak hour. It is interesting to note that the 80th percentile PTI is lower for the HOT lanes for all of the investigated hours, including the peak hour at 5:00 PM, and that the difference in reliability between the GP and HOT lanes is higher when the comparison is based on the 80th percentile PTI compared to when measured based on the 95th percentile PTI. This again indicates that non-recurrent events contribute more to the variability of HOT lanes compared to their contributions to the variability of the GP lanes since the comparison based on the 80 th percentile PTI excludes the extreme events normally associated with nonrecurring congestion from the comparison.

A similar trend to those observed with the PTI measurements discussed above was observed with the Misery Index, as indicated in Figures 2 and 3. For the GP and HOT lanes, the Misery Index values are lower in the uncongested periods compared to the congested periods, as expected. The

Misery Index of the HOT lane is lower than that of the GP lanes prior to the peak hour but exceeds it at the peak hour. This is another indication that extreme non-recurrent events contribute more to the variability of the HOT lanes compared with that of the GP lanes at the peak hour since the Misery Index measures the travel time for the worst 5% travel time estimates.

The results of examining the other measures do not show the consistent trend of increase with the increase in congestion, observed when examining the PTI and the Misery Index in the discussion above. Figure 3 shows that the BI metric for the GP lane is not sensitive to the increase in congestion. BI is computed as the difference between the 95th percentile and the mean divided by the mean travel time. The BI value of the GP lanes remains almost constant during the peak period because, although the variability of travel time increases significantly as the peak demand approaches the values of the numerator in the BI calculations, the travel time mean (or median) also increases as the congestion increases. For the GP lanes, the rate of change of the travel time mean/median parameter is close to the rate of change of the difference between the 95th percentile and the mean/median travel time resulting in BI values that remain almost constant. In the case of the HOT lanes, the rate of increase in the variability of travel time with the increase in congestion is higher than the rate of the increase in the mean/median resulting in an increase in the BI. The inconsistency and lack of sensitivity of the BI to the increase in congestion in some cases may limit its use, at least for some reliability assessment and analyses tasks.

The Failure/On-Time metric (FOT) represents the number of occurrences of travel time that are lower than the median travel time times a factor (1.1 or 1.25). The implication is that the higher is this metric, the more reliable is the system because more of the travel time instances are close to the median. The value of this metric is affected by both the median and standard deviation values. As discussed previously, as the congestion increases both the median and standard deviation increases. The results shown in Figures 2 and 3 indicate that there is no clear trend of the time-variant trend of FOT metric with the increased congestion since the change in the metric value from one step to the next depends on how the rate of change in the median value is compared with the rate of the change in the standard deviation for the facility under consideration.

The trend of the Skew Statistic with the increase in congestion is also not very clear. It appears to be a function of the relative contributions of different sources of unreliability to the total travel time variability. For the GP lanes, it is clear that the value of this metric is lower at higher congestion levels indicating more symmetrical distributions due to the higher contribution of the recurrent evens to the overall variability of the systems that is impacted heavily by the high day-to-day variations due to recurrent congestion. The variations due to recurrent congestion are typically characterized by more symmetrical distribution (less skewed distributions), as described earlier. For HOT lanes, the Skewness Statistics initially increases as the shoulders of the peak hour are reached indicating the higher impacts of each non-recurrent event on congestion due to the increase in demand as the shoulder of the peak is approached. However, as the demand is sharply increased in the peak hour itself, he variability of the travel time on the HOT lane becomes more influenced by the more symmetrical variability associated with recurrent congestion, causing the Skewness Statics to drop sharply.

Figure 2: Reliability metrics variation with time-of-day GP lanes

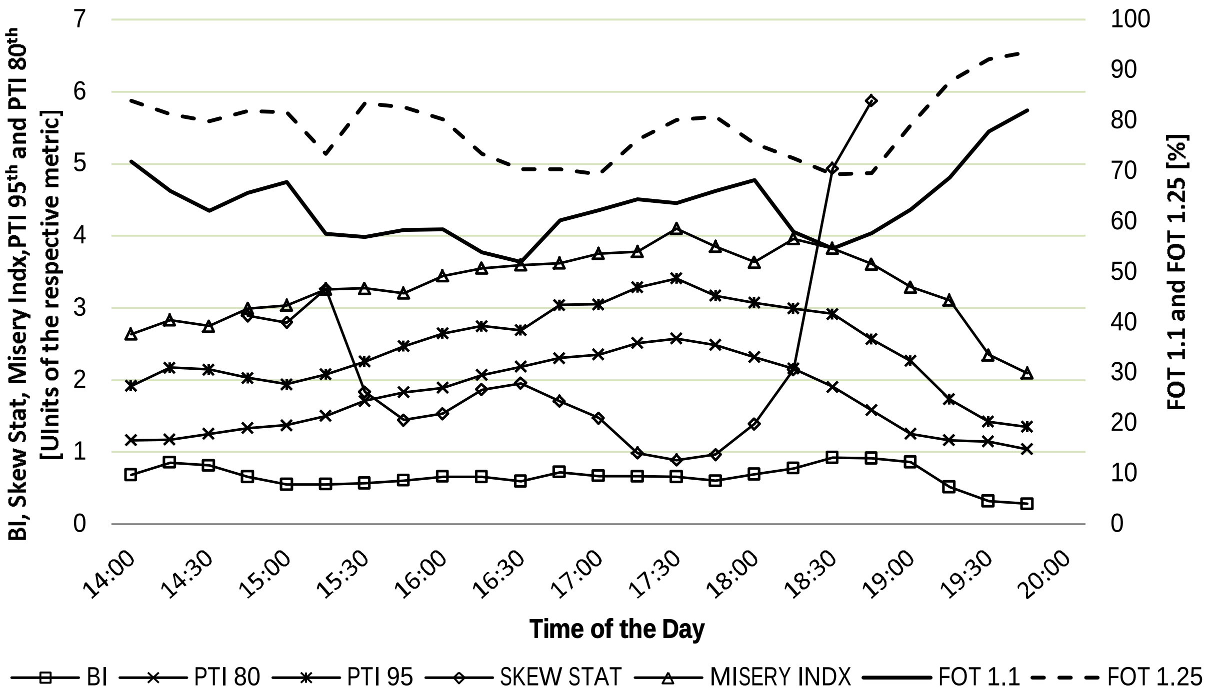
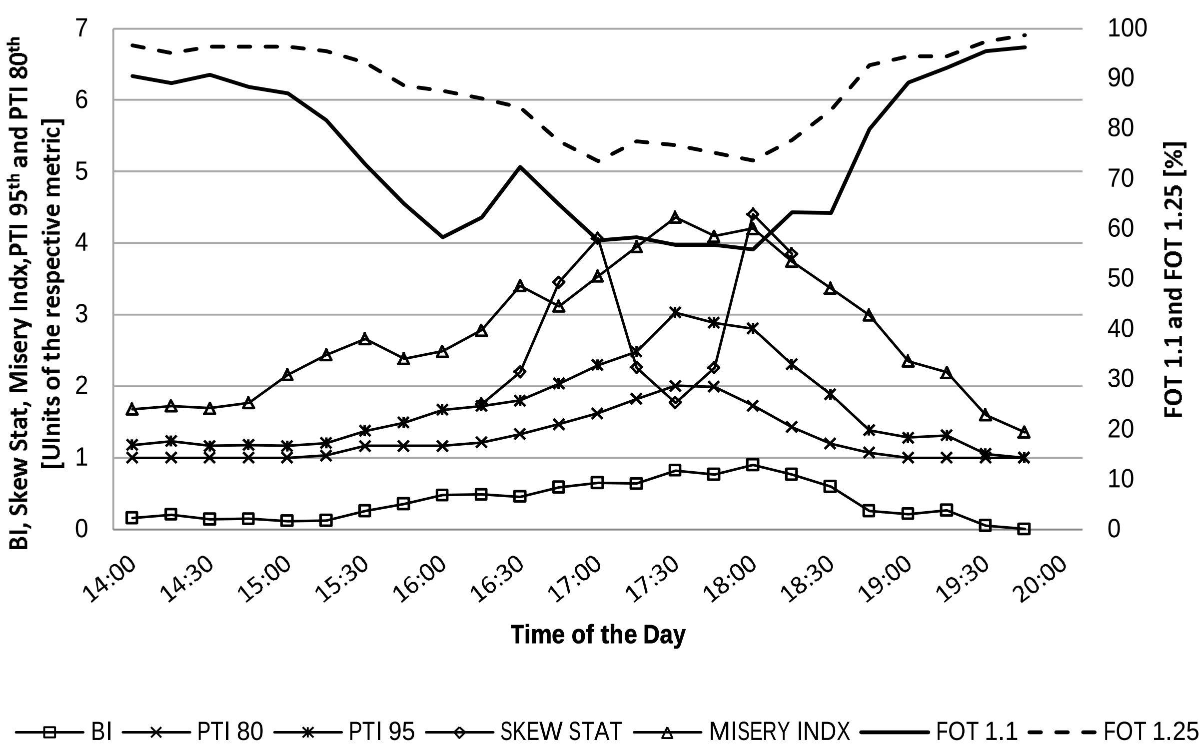


Figure 3: Reliability metrics variation with time-of-day HOT lanes



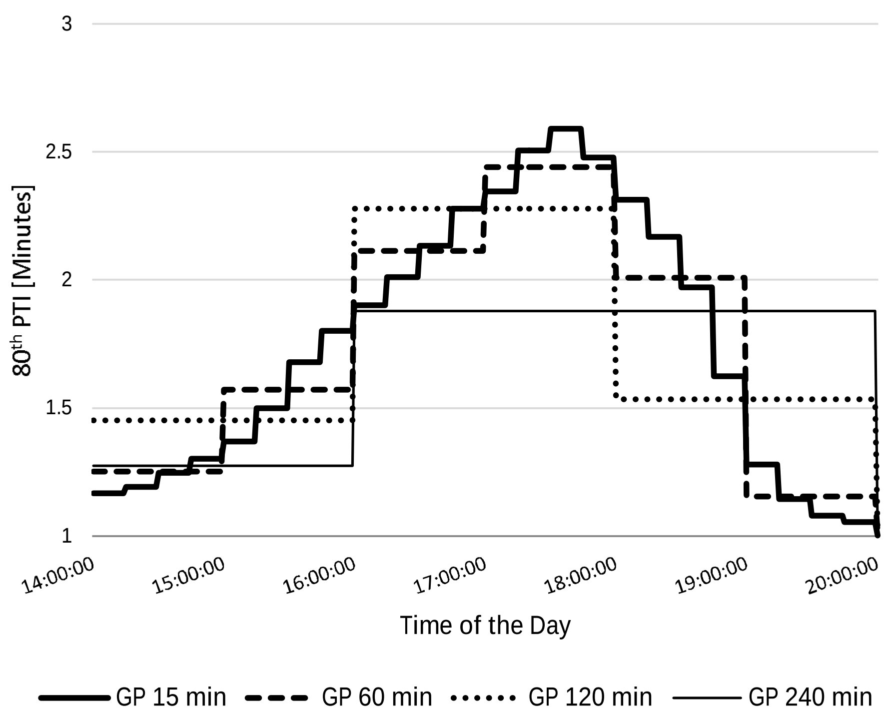
5 ANALYSIS PERIOD LENGTH

The discussion presented in the previous sections of this paper indicates that there is a considerable variation in the travel time distributions parameters and travel time reliability metrics when these parameters and metrics are estimated for different time intervals of the peak periods. This section addresses the effect of the choice of the time of day analysis interval (segmentation of the peak period into subintervals) on the calculated metrics.

The available data allows estimating travel time for every minute of the day. However, it may not be useful to produce the reliability metrics for every minute. At the same time, as can be concluded from the earlier discussion, it may not be appropriate to compute the metrics to represent long periods of time. As stated earlier, existing analysis and modeling approaches utilize 15-30 minute intervals suggesting that segmenting the peak period into 15-30 minute intervals may be needed for estimating the reliability metrics for such applications.

In this study, the 80^{th} Percentile PTI metric was computed for analysis periods of 15 minutes, 15 minutes, 1 hour, 2 hour, and 4 hour and the results are presented in Figure 4. The results show that depending of the congestion levels, different aggregation periods may lead to significantly different assessments of the reliability. One effect of using more aggregated periods of time would be the dilution of the travel time variability during the period of interest, particularly during periods of varying congested levels. Another potential undesirable effect of such aggregation is the dilution of the relative differences between the facilities being compared such as the comparison of the GP and HOT lanes, conducted in this study.

Figure 4: Impact of aggregation levels on the 80th Percentile PTI metric



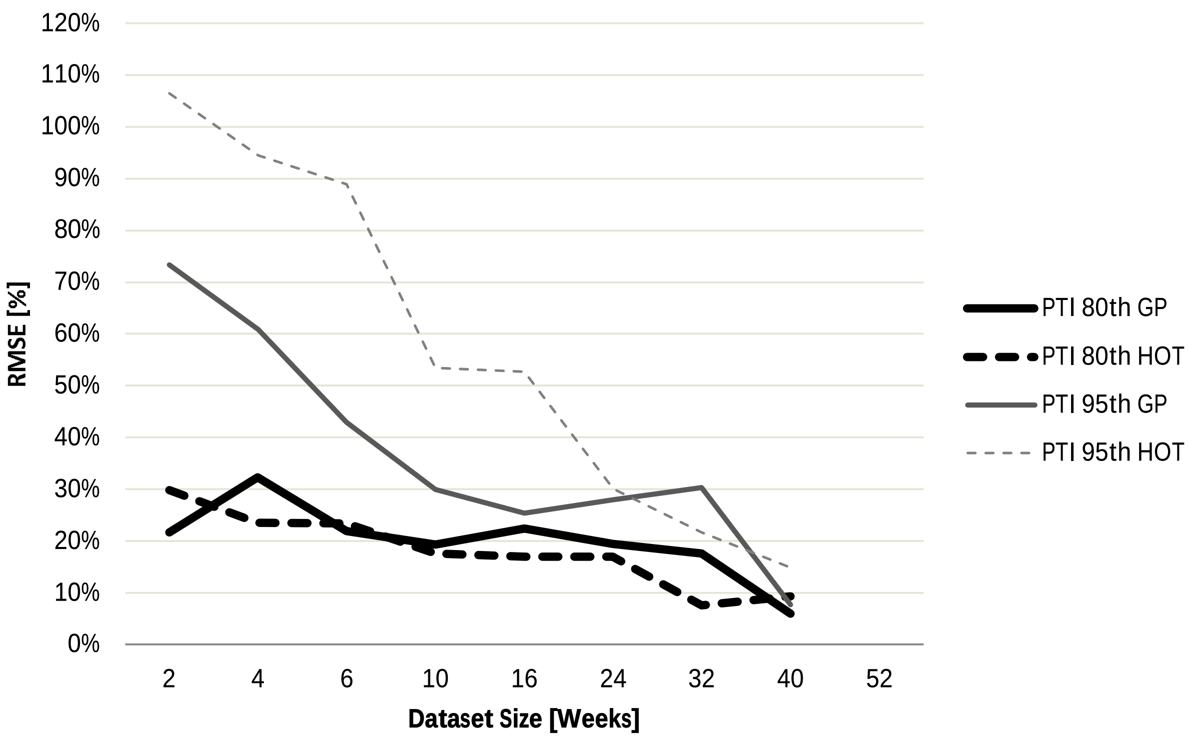
6 LENGTH OF DATA COLLECTION PERIOD

Another aspect of the travel time reliability researched is the length of the period for which the data is collected as it impacts the accuracy of the computed reliability metrics. This accuracy can be assessed compared to the accuracy achieved if the data is collected for a long period of time (a whole year in this study).

The analysis investigated the root mean square error (RMSE) between the values of the calculated reliability metrics based on data collected for each data collection period length and the metrics values calculated using a year's worth of data. The four measures are the 95th percentile and 80th percentile PTI for GP and HOT lanes. Figure 5 shows how the RMSE of the computed values of reliability measures varies with the number of weeks considered for reliability estimation. The figure shows that as the data collection period increases, the error relative to the estimates based on one year's data decreases. However, Figure 5 shows that even when collecting data for 40 weeks, the RMSE is still at least 10% and as high as 18% for the investigated measures. The SHRP2 LO3 project recommended using at least 6 months and preferably a year's worth of data to estimate the reliability metrics. The results in Figure 5 confirm that at least one year's worth of data is needed to estimate stable values of the investigated reliability measures.

Based on the results of the study, at least one year of data is recommended for use to obtain stable values of reliability metrics.

Figure 5: Effect of data collection period length



7 CONCLUSIONS

There are several metrics of reliability that have been recommended for use. These metrics need to be calculated at relatively fine levels of aggregation of travel time data when used for advanced management strategies and analysis methods. The results show that the parameters of travel time distributions vary during the peak period reflecting the effects of the traffic congestion, traffic flow dynamics, and the proportion of the contribution of non-recurrent factors such as incidents to the unreliability of travel time on the investigated facility. Different trends of travel time variations are observed when using different reliability metrics to assess reliability as the congestion level changes during the peak period.

The results also show that examining combinations of time-variant static distribution parameters and reliability metrics of the GP and HOT lanes can provide valuable information that cannot be obtained when performing the analysis at higher aggregation levels. The 95th Percentile PTI, 80thPercentile PTI, and Misery Index showed continuity and sensitivity in their variations in response to the increase in variability as the congestion in the peak hour. The BI measure was insensitive to the increase in congestion on the GP lane but showed sensitivity to the congestion for the HOT lanes due to the difference in the rates of changes of standard deviations and medians of travel time with the increase of congestion on these facilities, indicating that the interpretation of the results based on this metric should be done with caution. The FOT and Skew Statistics showed inconsistent patterns of travel time variation with the increase in congestion on GP and HOT lanes reflecting the differences in the rates of the increase in the median and standard deviation rates of travel time with the increased congestion on the two facilities and the relative contributions of non-recurrent events to the unreliability.

The results also show that examining combinations of time-variant static distribution parameters and reliability metrics of the GP and HOT lanes can provide valuable information on the variations of the reliability of these facilities during the analysis periods and the levels of contribution of nonrecurring events to the unreliability at different times of the day.

The results from the study also confirmed that the use of at least 30 minutes period of analysis is preferable to using longer periods for applications that require fine-grained analysis in order to reasonably represent the reliability pattern during congested periods. In addition, the results from the study confirmed that at least one year's worth of data should be collected to obtain a more stable value of reliability metrics.

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