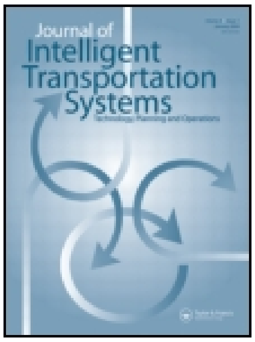

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Measuring Truck Travel Time Reliability Using Truck Probe GPS Data

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Truck probe data collected by global positioning system (GPS) devices has gained increased attention as a source of truck mobility data, including measuring truck travel time reliability. Most reliability studies that apply GPS data are based on travel time observations retrieved from GPS data. The major challenges to using GPS data are small, nonrandom observation sets and low reading frequency. In contrast, using GPS spot speed (instantaneous speed recorded by GPS devices) directly can address these concerns. However, a recently introduced GPS spot-speed-based reliability metric that uses speed distribution does not provide a numerical value that would allow for a quantitative evaluation. In light of this, the research described in this article improves the current GPS spot speed distribution-based reliability approach by calculating the speed distribution coefficient of variation. An empirical investigation of truck travel time reliability on Interstate 5 in Seattle, WA, is performed. In addition, correlations are provided between the improved approach and a number of commonly used reliability measures. The reliability measures are not highly correlated, demonstrating that different measures provide different conclusions for the same underlying data and traffic conditions. The advantages and disadvantages of each measure are discussed and recommendations of the appropriate measures for different applications are presented.

Keywords Coefficient of Variation; Correlation; GPS Spot Speed Distribution; Truck Probe GPS Data; Truck Travel Time Reliability

INTRODUCTION

Travel time reliability represents the level of consistency in travel times for the same trip for a time period (Lomax et al., 2003). It has been recognized as a critical factor in truck routing and scheduling. A survey conducted by Bogers and van Zuylen (2004) found that truck drivers prefer the more reliable route, even if it involves a longer trip in comparison to other routes with shorter travel time and higher uncertainty. While travel time reliability is a factor for determining truck route choice, it is also becoming an important component of freight mobility performance metrics (Cambridge Systematics, 2013; U.S. Department of Transportation [U.S. DOT], 2006). Given the importance of travel time reliability, numerous quantitative approaches have been proposed to measure travel time reliability based on a variety of data sources. The truck probe data collected from global positioning system (GPS) devices have gained increased attention as a source of truck travel time reliability input given the growing market penetration of GPS technology, as well as the improved truck -pecific vehicle location and speed information provided by GPS devices. Meanwhile, the Moving Ahead for Progress in the 21st Century (MAP-21) program will make GPS data from commercial vehicles available to transportation agencies for evaluating regional freight performance, including travel time reliability.

Most truck travel time reliability studies that apply GPS data are based on travel time observations that are retrieved from GPS data (American Transportation Research Institute (ATRI) and Federal Highway Administration [FHWA], 2005; Figliozzi et al., 2011; Liao, 2009; U.S. DOT, 2006, 2010). The travel time observations require substantial sample size to ensure statistical reliability (National Cooperative Highway Research Program [NCHRP], 2008; Figliozzi et al., 2011), and the major challenges to using GPS data to obtain travel times are small, nonrandom observation sets and low reading frequency. In contrast, using GPS spot speed directly can

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alleviate the low read rate and read density concerns. In addition, raw GPS data typically provide spot speed (not travel time), and the conversion from spot speed to travel time for a particular segment involves data processing and therefore may cause a loss of data accuracy. Despite the potential of truck GPS spot speed data to support truck specific travel time reliability assessment, there are limited studies investigating reliability metrics based on spot speed data. Zhao, McCormack, Dailey, and Scharnhorst (2013) developed the GPS spot speed distribution-based approach to evaluate truck travel time reliability and identified bottlenecks based on the hypothesis that the truck speed distribution can be modeled by either unimodal or bimodal probability density functions. They further identified that if truck speed follows a bimodal distribution, the segment is classified as unreliable. Otherwise, it is defined as reliable. However, this reliability metric only classifies reliability into three categories: reliably slow, reliably fast, and unreliable. It does not provide a numerical value that would allow for a more quantitative evaluation, for example, ranking reliabilities on different segments or during different time periods, or quantifying the changes in travel time reliability associated with transportation investments.

In light of this, the objective of this article is to improve the current GPS spot-speed-based reliability metric by proposing a means to support more quantitative analyses. In addition, the authors compare the proposed approach with a number of commonly used travel-time-based reliability measures: travel time coefficient of variation (COV), buffer time index (BI), skew, and truck reliability index (RI_{80}). The appropriate reliability measures for different applications are discussed. The remainder of this article is organized as follows: The second section provides a brief review of the commonly used travel time reliability measures that are implementable with truck GPS data, and discusses the sample size constraint associated with travel-time-based reliability measures; the third section proposes the improvement to the recently proposed GPS spot-speed-based approach; the fourth section applies the improved GPS spot-speed-based measure and those widely applied travel-time-based metrics to a case study and compares the correlations among these reliability measures; and the fifth section offers findings and conclusions of the analyses.

LITERATURE REVIEW ON CURRENT TRAVEL TIME RELIABILITY MEASURES

There has been substantial effort to develop travel time reliability measures relying upon statistical techniques and probe data collected from GPS devices. Comprehensive overviews of travel time reliability measures can be found in Lomax et al. (2003), NCHRP Report 618 (2008), and Cambridge Systematics (2013). Several commonly applied reliability measures are reviewed in this section since they can be measured and implemented with GPS data and have been tested and applied in practical projects. The authors classified these measures into two categories according to the data on which these approaches are based: travel-time-based reliability measure and GPS spot-speed-based measure.

Travel-Time-Based Reliability Measures

Standard Deviation and Coefficient of Variation (COV)

The travel time standard deviation is a measure of how much spread observations have. The larger the value of the standard deviation, the lower is the travel time reliability. In addition to the standard deviation, the ratio of the standard deviation and the mean, also called the coefficient of variation, is defined as a reliability measure. This value is interpreted as the larger the standard deviation relative to the mean, the lower is the travel time reliability. One example of the use of the COV approach is the research led by the U.S. Department of Transportation (U.S. DOT) on measuring the crossing-border truck travel time and travel time reliability (U.S. DOT, 2010). The study location was the Otay Mesa International Border between the United States and Mexico. Truck GPS data were collected from January 2009 to February 2010. A large travel time standard deviation from the mean was observed, which ranged from 61 to 81% of the mean value. Therefore, the study concluded that carriers crossing the border experienced very low travel time reliability.

Percentile Method

In this method, the 95th percentile travel time was recommended by U.S. DOT as the metric to compare travel time reliabilities on different segments (Texas Transportation Institute [TTI] & Cambridge Systematics, Inc., 2006). This 95% travel time method is used to measure very long travel times based on observations over a certain time period, for example, across 1 year. It estimates the time that travelers need to plan in order to meet a desired arrival time. It is also called planning time. It is recommended by the National Cooperative Highway Research Program (NCHRP) as the simplest indicator of travel time reliability (NCHRP, 2008). Researchers may also use the 80th or 85th or other percentiles as the base. The SHRP 2 (Second Strategic Highway Research Program) recommended using 80th percentile travel time instead of 95th percentile travel time since it found that events that contribute to the 80th percentile travel time are more common events and are more likely to be influenced by operation strategies, such as improvement to transportation infrastructures (Cambridge Systematics, 2013). Figliozzi et al. (2011) evaluated travel time reliability along the Interstate 5 (I-5) corridor through the state of Oregon based upon truck GPS data accessed from the American Transportation Research Institute (ATRI). The 50th, 80th, and 95th percentile travel time were selected as metrics to measure travel time reliability along the I-5 corridor.

Buffer Time Index (BI)

Buffer time is defined as the extra travel time travelers must add to the average travel time to allow for on-time arrival, and it is calculated as the difference between the 95% travel time and average travel time (TTI & Cambridge Systematics, Inc., 2006). The buffer time index (BI) is calculated by dividing buffer time by the mean travel time. Federal and regional transportation agencies have used the BI to evaluate system performance. The Federal Highway Administration (FHWA) and ATRI have evaluated how information retrieved from GPS devices could provide data to support freight travel time reliability measures. The BI measure was employed to evaluate freight travel time reliability along five major freight corridors in the United States (U.S. DOT, 2006). The Minnesota DOT evaluated freight performance along I-94/I-90 from the Twin Cities to Chicago using archived truck GPS data, and freight travel time reliability was evaluated using the BI metric (Liao, 2009).

Skew

While standard deviation and COV represent the spread of the travel time distribution, the skew depicts the "leaning" of travel time distribution to one side of the mean. Van Lint and van Zuylen (2005) examined the travel time distribution along a 19.1-km freeway in the Netherlands and found that both width and skew of travel time distribution change with respect to different traffic regimes (van Lint, van Zuylen, & Tu, 2008). The travel time distribution is approximately symmetric before congestion, with small values of both width and skew. The distribution tends to be left-skewed, with wider breadth (longer tail) during the onset of congestion. During the congested period, the travel time distribution growths wider and becomes right-skewed. Finally, while congestion wanes, both the median travel time and the spread of travel time distribution decrease, and the distribution is left-skewed again (van Lint et al., 2008). Given the changes in both width and skew, van Lint and van Zuylen (2005) suggested that not only the variance of travel time should be used as a reliability measure, but also the skewness. The skewness is quantified by comparing how much of the 90th percentile travel time is greater than the median to how much the 10th percentile travel time is less than the median, as expressed in Eq. 1 (van Lint & van Zuylen, 2005, van Lint et al., 2008):

$$Skew = \frac{T_{90} - T_{50}}{T_{50} - T_{10}} \quad (1)$$

Truck Reliability Index (RI80)

The reliability measure recommended by the American Association of State Highway and Transportation Officials (AASHTO) for the MAP-21 Program is the RI_{80}, which is defined as the ratio of the total truck travel time needed to ensure on time arrival to the agency-determined congestion threshold travel time (e.g., observed travel time or preferred travel time; AASHTO, 2012; Cambridge Systematics, 2013). The 80th percentile travel time is chosen to represent the total truck travel time needed. The congestion threshold travel time is determined by each transportation agency and should account for various reasons to slowing trucks, for example, weather, congestion, accident, and work zone.

Different from the aforementioned measures quantifying travel time reliability, some other methods focus on users' perception of network reliability. For instance, Al-Deek and Emam (2006) developed a methodology to measure transportation network reliability by considering the effect of travel demand variability and corresponding link capacity degradation. This approach is sensitive to users' perspective, as it reflects an increase in travel time results in reduction in segments reliability. This approach requires the knowledge of travel quality expectation from users, which is not available from GPS data. Thus, this article focuses on travel time reliability measures that are measurable using GPS data.

Sample Size Constraint

The reliability measures discussed earlier rely upon travel time observations. Two common approaches are utilized to compute the travel times on a specific roadway segment using GPS data. One is the vehicle location-based approach. Two buffers are created at the segment start and end points, respectively, and truck trips that have GPS reads in both buffers are identified. The difference between the two time stamps in the two buffers is viewed as the travel time along the segment (Figliozzi et al., 2011). Another approach is the "estimated link speed" method (Zhao et al., 2011). This method is based upon the assumption that averaged GPS spot speed is able to approximate the travel speed along the segment when the segment is short, and consequently the travel time can be approximated by dividing the segment length by the average spot speed. Both approaches require sufficient travel time observations to ensure the estimated travel time can represent the link travel time with reasonable accuracy. The minimum number of travel time observations is proposed to ensure statistical reliability, and it is determined by the precision desired by the analysts and the variability of the data set (NCHRP, 2008). If analysts need to know the average travel time very precisely and the variability of the observations is high, for example, during peak period, a large number of observations will be required. The minimum required number of observations is shown in Eq. 2 (NCHRP, 2008):

$$N = 4 \times \left[t_{(1-\alpha/2),N-1} \times \frac{S}{CI_{1-\alpha\%}} \right]^2 \quad (2)$$

where N is the minimum required number of observations, $CI_{1-\alpha\%}$ the confidence interval for the true mean with probability of (1 – α)%, where α equals the probability of the true mean not lying within the confidence interval, $t_{(1-\alpha/2),N-1}$ is the t statistic for the probability of two-sided error summing to alpha with $N-1$ degrees of freedom, and S is the standard deviation in the measured travel times.

If the number of minimum observations is not reached, analysts need to either extend the time period, for example, from a 30-minute to a 1-hour interval, or increase the length of the segment being studied. However, for some segments with sparse GPS data sets and low data reading frequency, the minimum sample size cannot be achieved even if the analysis time period is extended to 3 hours. Also, the length of the segment should not be too long since roadway segmentation is mainly determined by the changes in truck volume, roadway geometric design and traffic control to ensure similar roadway characteristics.

GPS Spot-Speed-Based Approach

Sample size is often a challenge when producing travel time-based reliability metrics of statistical strength. To alleviate the challenges, Zhao et al. (2013) developed a GPS spot speed distribution-based approach, which provides a reliability measure with a sparse GPS data set. The Washington State Department of Transportation (WSDOT) has evaluated the truck reliability performance and identified freight bottlenecks using this approach (McCormack, Scharnhorst, & Zhao, 2011). The probe data used in Zhao's research are sparse for most segments, and are not sufficient to provide a travel time distribution to support travel time reliability analyses using the travel-time-based reliability methods reviewed in the preceding. Instead of examining the travel time distribution, they plotted the spot speed on each segment during certain time periods. It was found that a mixture of two Gaussian distributions provided the best fit for the truck speed observations. Zhao et al. (2013) assessed the reliability by evaluating the speed distributions with the assumption that the travel time is unreliable if bimodal distributions are observed. Otherwise (a unimodal distribution), it is classified as reliable. The probability density function of a mixture of two Gaussian distributions is shown in Eq. 3. The parameters are fitted based on the maximum likelihood rule:

$$f(x) = w \cdot n(x, \mu_1, \sigma_1) + (1-w) \cdot n(x, \mu_2, \sigma_2)$$
$$n(x, \mu_i, \sigma_i) = \frac{1}{\sqrt{2\pi}\sigma_i} \cdot \exp\left[-\frac{(x-\mu_i)^2}{2\sigma_i^2}\right] \quad (3)$$

where w is the proportion of the first normal distribution, μ_1 and μ_2 the mean of the first and second Gaussian distribution, and σ_1 and σ_2 the standard deviation of the first and second Gaussian distribution.

The approach defines the travel condition as unreliable if and only if $|\mu_1 - \mu_2| \geq |\sigma_1 + \sigma_2|$, $w \geq 0.2$, and $\mu_1 \leq 0.75 \times V_p$ (V_p is the posted speed); otherwise, it is viewed as reliable. For the reliable performance, it is subdivided into reliably fast and reliably slow depending on the average speed. The major advantage of this methodology is that the reliability evaluation does not require a large number of travel time observations, but rather only spot speed. However, the current method does not provide a numerical value, which would allow for a more quantitative evaluation and ranking.

The literature review section recalls a number of commonly applied travel time reliability measures. In contrast to the travel-time-based reliability measures, the reliability metric proposed in the next section is based on GPS spot speed data. It is an improvement to the newly proposed spot-speed-based approach discussed earlier, which allows more quantitative analyses.

IMPROVEMENT TO THE GPS SPOT SPEED BASED RELIABILITY MEASURE

As discussed in the previous sections, the current GPS spot-speed-based approach can only classify segment travel time reliability into three categories. For example, Figure 1 shows the fitted truck spot speed distributions of four segments during the a.m. peak period (6:00 a.m.–9:00 a.m.) based on GPS observations collected in May 2012. Segment 1 and Segment 2 are the stretch of 9 miles of eastbound and westbound of Interstate 90 (I-90) near Spokane, WA. Segment 3 and Segment 4 are the stretch of 3.5 miles of southbound and northbound of Interstate 5 (I-5) near downtown Seattle, WA. The corresponding fitted parameters are given in Table 1. The distribution fitting was accomplished using the R software package "mixdist" (Du, 2002). Taking Segment 1 as an example, the fitted result can be interpreted as follows. The GPS spot speed distribution is composed of two traffic regimes. The average truck travel speed of the first traffic regime is 40.05 mph, with standard deviation of 21.6 mph. The average truck travel speed of the second traffic regime is 63.36 mph, with standard deviation of 5.11 mph. The probability of truck travel speed falling within the first traffic regime is 4%, which indicates that the probability of truck travel speed falling within the low-speed regime is very small. Since the fitted parameters do not meet the rule of "$|\mu_1 - \mu_2| \geq |\sigma_1 + \sigma_2|$ and $w \geq 0.2$," the travel time distribution of segment 1 follows a unimodal distribution (as shown in Figure 1a). In addition, the average travel speed is 62.29 mph, which is greater than the 75% of the posted speed limit. Thus, travel time on Segment 1 is further defined as reliably fast. Similarly, the truck travel time on Segment 2 is also defined as reliably fast. For Segment 3, it is also composed of two traffic regimes. The average truck travel speed of the first traffic regime is 24.01 mph, with standard deviation of 11.78 mph. The average truck travel speed of the second traffic regime is 54.44 mph, with standard deviation of 6.19 mph. The probability of truck travel speed falling within

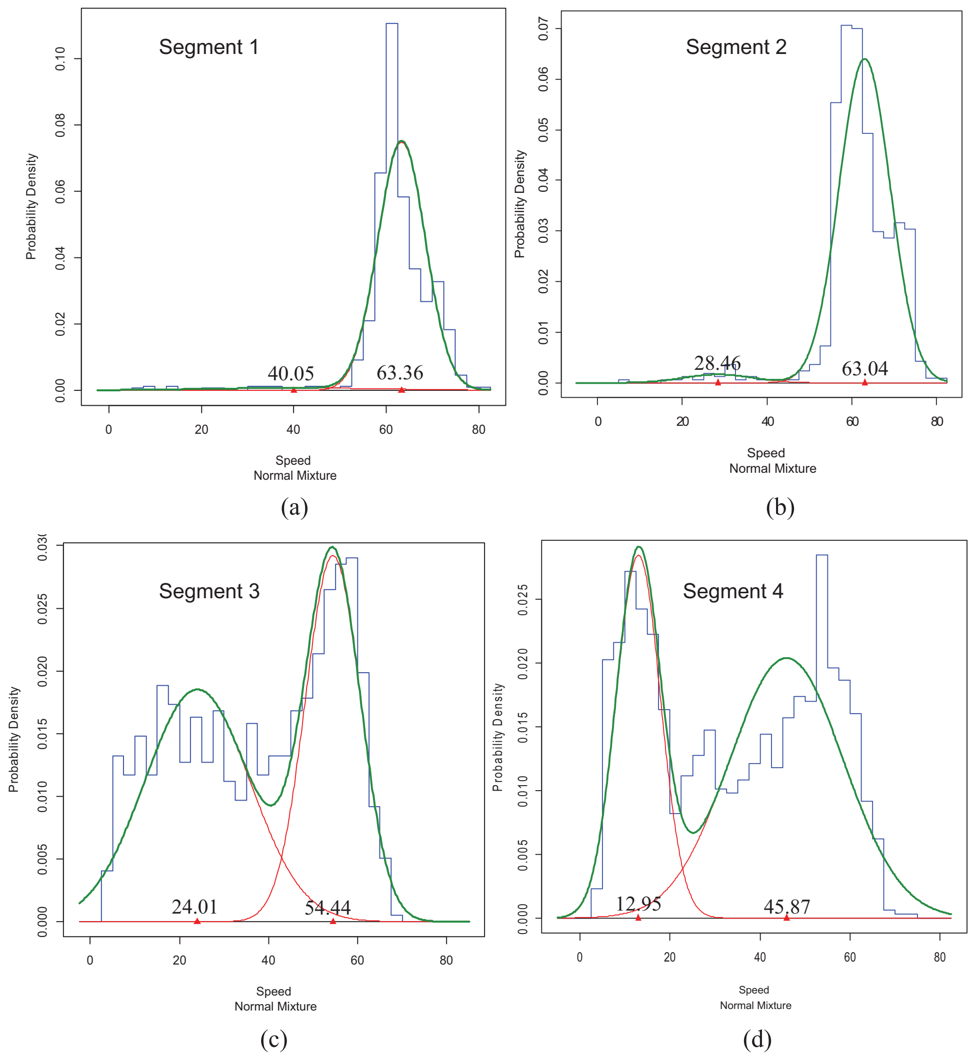

Figure 1 GPS spot speed distribution fittings of four segments during a.m. peak period.

the low-speed traffic regime is 55%. The fitted parameters meet the predefined rule, and therefore the travel time on Segment 3 is defined as unreliable during the a.m. peak period. Similarly, Segment 4 is defined as unreliable. However, this approach can only identify the reliability category, but it is not able to rank the reliabilities to identify the most unreliable segment.

A coefficient of variation (COV) method is proposed to improve the current approach. Since it has been proven that the GPS spot speed distribution follows a mixture of two

Table 1 Estimated parameters for GPS spot speed distribution fittings of four segments.

	Segment 1	Segment 2	Segment 3	Segment 4
W	0.04	0.03	0.55	0.35
μ_1	40.05	28.46	24.01	12.95
σ_1	21.60	8.16	11.78	4.94
μ_2	63.36	63.04	54.44	45.87
σ_2	5.11	6.02	6.19	12.65
V_p	60	60	60	60
Average speed	62.29	61.84	37.52	34.16
if $\lvert\mu_1-\mu_2\rvert \geq \lvert\sigma_1+\sigma_2\rvert, w\geq 0.2$ *and* $\mu_1 \leq 0.75 \times V_p$	No	No	Yes	Yes
if average speed $\leq 0.75 \times V_p$	No	No	—	—
Reliability category	Reliably fast	Reliably fast	Unreliable	Unreliable

Table 2 Reliability measurements and ranking results of the four segments.

	Segment 1	Segment 2	Segment 3	Segment 4
Mean	62.43	62.00	37.70	34.35
Standard deviation	8.04	8.48	17.97	18.95
COV	0.13	0.14	0.48	0.55
Reliability ranking	4	3	2	1

Gaussian distributions, the mean and standard deviation of the spot speed distribution can be calculated based on the parameters of the two distributions, as shown in Eq. 4. The COV, which is computed by dividing the standard deviation by the mean, is employed as travel time reliability measure, as shown in Eq. 5:

$$\mu = \sum_{i=1}^{n} w_i \mu_i$$
$$\sigma^2 = \sum_{i=1}^{n} w_i((\mu_i - \mu)^2 + \sigma_i) \tag{4}$$

$$Coefficient\ of\ Variation(COV) = \frac{\sigma}{\mu} \tag{5}$$

where μ is the mean of the mixture of Gaussian distributions, w_i= weight of the ith Gaussian distribution, μ_i the mean of the ith Gaussian distribution, σ the standard deviation of the mixture of Gaussian distributions, σ_i the standard deviation of the ith Gaussian distribution, n the number of Gaussian distributions, and $n = 2$ since it has been proved that spot speed follows of the mixture of two Gaussian distributions.

Using Eq. 5, the corresponding COV of the four segments can be computed, as displayed in Table 2. The authors ranked the travel time reliability based on the values of the COV, where 1 represents the least reliable segment and 4 represents the most reliable segment. The larger the standard deviation relative to the mean, the lower is the travel time reliability. According to the calculation, Segment 4 was identified as the most unreliable segment during the a.m. peak period based on the 1-month GPS spot speed observations, and Segment 1 was the most reliable segment. This information can be used to support resource allocation and planning.

GPS DATA-BASED TRAVEL TIME RELIABILITY MEASURES COMPARISON

This section provides a case study to compare various reliability measures by ranking the reliabilities on the same segment during different times of day and days of the week, and computing the correlation among these measures.

Study Area and Description of the Probe Data Used

A stretch of 3.5 miles of southbound Interstate 5 (I-5) through downtown Seattle was selected for the case study. Travel time reliability was examined during two time periods: off-peak period (12:00 a.m.–6:00 a.m.) and a.m. peak period (6:00 a.m.–9:00 a.m.). The GPS data acquisition efforts on which this article is based comprised a pilot study investigating how to gather and use existing GPS data collected for truck fleet management to develop performance measures for trucks (McCormack, Ma, Klocow, Currarei, & Wright, 2010). The GPS data were initially collected by a GPS vendor for trucking companies' fleet management. The data are purchased from the GPS vendor directly, and they include a unique device identification (ID), vehicle trajectory, spot speed, heading, location (latitude and longitude), time, and date. Each device ID was scrambled for anonymity to protect the customer information. Data were collected from January 2012 to December 2012. More details of data collection efforts can be found in McCormack et al. (2010), Ma et al. (2011), and McCormack et al. (2011). The average GPS reading frequency ranges from every 2 to every 15 minutes. Chase, Williams, Rouphail, and Kim (2012) found that difference in travel time aggregation intervals impacts the accuracy of travel time estimates. Zhao (2011) evaluated the accuracy of the same GPS data used in this article in estimating travel time comparing to loop detector data-based travel time estimates. It is found that this GPS data set is a reliable data source to generate acceptable travel time. The GPS data processing consists of three steps: (1) cleaning data to filter out problematic and duplicated data, (2) geocoding GPS data to road segments, and (3) estimating travel time from GPS spot speed (if travel-time-based reliability measures are selected). More details of the data processing and travel time estimation can be found in McCormack et al. (2011) and Zhao et al. (2011).

The traffic performance information retrieved from the GPS data set represents the performance of trucks equipped with GPS devices. Previous research by Zhao et al. (2011) has demonstrated that the mean truck travel speed computed from the GPS data compared well with the mean mixed traffic speed recorded by loop detectors deployed in the right-most lane (the absolute differences between the two values are less than 6%). The MAP-21 program will provide state DOTs with GPS for performance measures. Although the GPS data may be provided by different vendors than that described in this article, the data formats are consistent with those identified in this article.

Table 3 Reliability ranking results.

Measures	Monday	Tuesday	Wednesday	Thursday	Friday
(a) Reliability ranking results during off-peak period (12:00 a.m.–6:00 a.m.).					
COV	2	5	4	3	1
BI	3	5	2	4	1
Skew	3	5	4	2	1
RI_{80}	3	5	2	4	1
Improved GPS spot-speed-based method	3	5	2	4	1
(b) Reliability ranking results during a.m. peak period (6:00 a.m.–9:00 a.m.).					
COV	1	4	2	3	5
BI	4	5	3	1	2
Skew	1	4	5	3	2
RI_{80}	4	3	2	1	5
Improved GPS spot-speed-based method	4	2	1	3	5

Reliability Ranking Results

Truck travel time reliability on the selected segment was measured using a number of reliability metrics: COV, BI, skew, RI_{80}, and the improved GPS spot-speed-based method. The travel time standard deviation method was not included in the case study since it is highly correlated to the COV. The RI_{80} was calculated by dividing the 80th percentile travel time by 60% of posted speed (Washington State Department of Transportation congestion threshold; WSDOT, 2010). The 80th percentile travel time measure was not included in the analysis as it is highly correlated with the RI_{80} metric.

Table 3 shows the reliability ranking results of the same segments during different times of day and days of the week, each based on one of the reliability measures listed earlier.

The travel time reliability ranking results vary depending on the measures used. During the off-peak period, all measures identify travel time on Friday as the least reliable and travel time on Tuesday as the most reliable. However, the rankings of the rest of three days are different. The rankings differ significantly during the a.m. peak period. The COV and skew metrics indicate that travel time on Monday is the least reliable compared to other days, the BI and RI_{80} method show that truck drivers experienced the most unreliable travel time on Thursday, and travel time on Wednesday is defined as the most unreliable by the improved GPS spot-speed-based approach. The differences stem from the fact that different measures capture different components of reliability.

Correlations Among Travel Time Reliability Measures

The preceding ranking results indicate that different measures get different conclusions even if the same data are used. To further explore the relationship among these measures, the correlations among each measure were calculated, as displayed in Table 4. The values represent the degree to which these measures are related.

Although the preceding results are based on a specific freeway segment truck travel time and speed data, they reveal a general finding that there are large deviations among the travel-time-based reliability measures, and between the travel-time-based reliability measures and the improved GPS spot-speed-based approach. What's more, the deviations are more significant during peak period compared to off-peak period.

The COV and skew are not highly related during the off-peak period (with correlation of 0.666), and they are even more weakly related during peak period (with correlation of 0.471). By examining the definitions of the two measures, we see that they capture different characteristics of the travel time distribution. The COV evaluates the width or spread of travel time distribution, while the skew depicts the leaning of travel time distribution. It is not necessarily the case that a small variance is associated with small skew, especially when the travel time distribution is highly left-skewed (during congestion onset and congestion dissolve regimes).

The COV is not closely related to the BI either. This is because the BI is computed based on the difference between the extreme travel time (80th percentile travel time) and the average travel time. The smaller difference between the extreme travel time and average travel time is not necessarily related to a small COV since a few extreme values affect the mean more significantly than the extreme travel time, for example, 80th, 90th, and 95th percentile travel times (Cambridge Systematic, 2013). This is explained in Figure 2, which displays two travel time distributions. The first distribution contains some extreme travel time values, and the distribution is left-skewed. The second one represents the distribution after removing those extreme values. The traffic performance of the second condition is more reliable than the first one and generates smaller COV. However, as shown in Figure 2, the corresponding BI of the second condition is greater than the first one. This may explain the weak correlation between COV and BI. As a result, several studies suggested computing BI by using median travel time instead of mean travel time (Cambridge Systematics, 2013, Pu, 2010).

Table 4 Correlations among reliability measures.

	COV	BI	Skew	RI_{80}	Improved GPS spot speed
(a) Correlations among reliability measures during off-peak period.					
COV	1.000				
BI	0.639	1.000			
Skew	0.666	0.408	1.000		
RI_{80}	0.695	0.735	0.446	1.000	
Improved GPS spot speed	0.556	0.433	0.420	0.769	1.000
(b) Correlations among reliability measures during a.m. peak period.					
COV	1.000				
BI	0.679	1.000			
Skew	0.471	0.418	1.000		
RI_{80}	0.508	0.595	0.135	1.000	
Improved GPS spot speed	0.322	0.196	−0.223	0.821	1.000

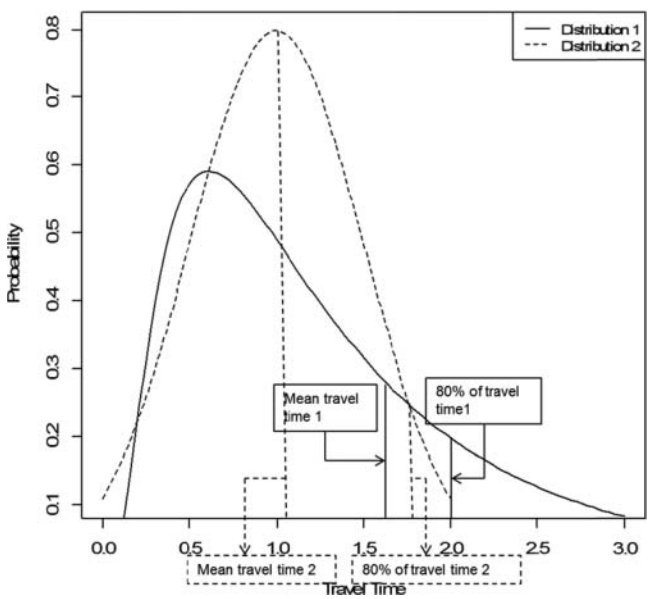

Figure 2 Mean and 80th percentile travel time of two distributions.

The improved GPS spot speed approach is computed as the coefficient of variation of the speed distribution. However, the travel-time-based COV metric is not highly related to the improved GPS spot speed approach either. This may due to the loss of data accuracy during the conversion from GPS spot speed to travel time estimations.

The correlation analysis reveals that different measures provide different conclusions for the same underlying data and traffic conditions, and judgment as to whether or not a particular segment is reliable depends on the reliability measures used. Table 5 presents the comparison of each measure. The selection of the appropriate measures depends on the characteristics of each measure discussed earlier, as well as the available data set, potential users, and analysis purposes.

As summarized in Table 5, if raw GPS data are readily available, the GPS spot speed approach is preferred as it does not require additional data processing efforts to retrieve travel time estimates from raw data. It is an asset to avoid this task, as it requires resources and provides opportunities for introducing error. For state DOTs and other transportation agencies, when travel time observations are readily available, and if the intent of the analysis is to rank reliability on different

Table 5 Comparison of travel time reliability measures.

	SD and COV	Percentile method	BI	Skew	RI_{80}	GPS spot-speed-based approach
Does not require conversion of original data into travel time estimate.						×
Smaller sample size requirement.						×
Has been widely applied.	×	×	×			
Easy to compute when historical travel time observations are available.	×	×	×	×	×	
Easy to interpret to nontechnical users.		×	×			
Ability to be applied for daily trip planning.		×	×			
Ability to compare reliability across trips and segments.			×		×	×
Ability to indicate whether congestion is increasing or decreasing.				×		

segments or identify truck bottlenecks, the SD, COV, and RI_{80} are recommended as they are easy to compute and provide quantitative measures to rank reliability. If the real-time data are available and the analysts aim to propose efficient traffic operation strategies to alleviate traffic congestion, the skew could be considered due to its capability in capturing short-term traffic trends. For a nontechnical audience, the percentile method and the mean value-based BI are ideal measures for trip planning, for example, determining departure time and vehicle routing for freight industry.

FINDINGS AND CONCLUSIONS

This article recalls a number of reliability measures that are implementable with truck GPS data. These measures are classified into two categories: the travel-time-based measures and spot-speed-based measures. GPS data sample size is one of the major concerns of implementing the travel-time-based measures with sparse GPS observations. In addition, truck GPS data usually provide instantaneous speed and the conversion from spot speed to travel time estimates requires additional efforts, and therefore may cause loss of data accuracy. The recently proposed GPS spot-speed-based approach can alleviate the sample size constraint, and it does not require data processing from spot speed to travel time estimates. However, it is not able to provide a quantitative means for ranking and comparing reliabilities. Thus, an improvement was made to provide a means for more quantitative analyses by calculating the spot speed distribution COV. The improved spot-speed-based reliability measure is able to provide numerical values that allow for quantitative analyses.

The improved method was compared with a number of travel-time-based reliability measures. It is found that the assessment of reliability on a particular segment during periods depends on the reliability measures used. Different measures may get different conclusions for the same underlying data. Therefore, the ranking of travel time reliability bottlenecks varies depending on the reliability measures used, and even just those travel-time-based reliability measures do not obtain the same conclusion. The correlation calculation indicates that there are large deviations among reliability measures, and this is mainly due to the fact that these measures capture different components of reliability. For instance, the COV represents how spread the observations are, the BI captures the impacts of extreme values, and the skew reflects the leaning of travel time distribution to one side of the mean. Given the different characteristics of each measure, the selection of the appropriate measures for different applications is determined by the available data sets, potential users, and analysis purposes.

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