Estimating Reference Speed from Probe-based Travel Speed Data for Performance Measurement

by

Kartikeya Jha (corresponding author)
Graduate Research Assistant, Texas A&M Transportation Institute
The Texas A&M University System, 3135 TAMU
College Station, TX 77843-3135
Tel: 979-739-0529, Email: jha_k@tamu.edu

Mark W. Burris, Ph.D., P.E.
Herbert D. Kelleher Professor, Zachry Department of Civil Engineering
Texas A&M University, CE/TTI Building, Room No. 304-C
College Station, TX 77843-3136
Tel: 979-845-9875, Fax: 979-845-6481, Email: mburris@tamu.edu

William L. Eisele, Ph.D., P.E., PMP
Senior Research Engineer and Program Manager, Texas A&M Transportation Institute
The Texas A&M University System, 3135 TAMU
College Station, TX 77843-3135
Tel: 979-845-8550, Fax: 979-845-6008, Email: bill-eisele@tamu.edu

David L. Schrank, Ph.D.
Associate Research Scientist, Texas A&M Transportation Institute
The Texas A&M University System, 3135 TAMU
College Station, TX 77843-3135
Tel: 979-845-7323, Fax: 979-845-6008, Email: d-schrank@tamu.edu

Timothy J. Lomax, Ph.D., P.E.
Senior Research Engineer and Regents Fellow, Texas A&M Transportation Institute
The Texas A&M University System, 3135 TAMU
College Station, TX 77843-3135
Tel: 979-845-9960, Fax: 979-845-6008, Email: t-lomax@tamu.edu

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ABSTRACT

The federal *Moving Ahead for Progress in the 21st Century* legislation mandated a performance-based evaluation approach for transportation projects. Reference travel speed is used as a benchmark for calculating delay, mobility and reliability statistics in standard industry and research practice. These reference speeds reflect free-flow (unconstrained) travel conditions on different facilities. However, the rationale behind the choice of this important parameter is not entirely established and a few different metrics are adopted.

This study provides a basis for benchmarking reference speed for use in mobility and reliability performance measures. An average driver's perception of reference speed on a roadway segment is influenced not only by the posted limit but also a few other factors including road geometry and driving conditions. Therefore, recorded travel time data can be more reflective of current travel conditions on roadway segments than the posted speed limit. This research investigates an appropriate reference time window representative of unconstrained conditions by analyzing all-day travel patterns on different facilities.

Researchers find that nighttime hours (9PM-6AM) provide a good representation of unconstrained travel on both interrupted and uninterrupted flow facilities. When overnight data are inadequate, they can be supplemented with mid-day (11AM-4PM) unconstrained travel data. The 85th percentile of average speeds within identified time windows is the recommended reference speed metric for all roadway functional classes. On minor arterial streets, actuation and priority treatment cause lower nighttime travel speeds, therefore, the 85th percentile of supplemented data (nighttime and mid-day) is more representative of reference travel conditions on such facilities.

INTRODUCTION

The Moving Ahead for Progress in the 21st Century Act (MAP-21) propelled transportation system performance measurement to the center-stage within the transportation profession *(1)*. Several state departments of transportation (DOTs), public and private agencies, and metropolitan planning organizations (MPOs) have developed measures and techniques to actively evaluate and address their roadway infrastructure's ability to meet planned objectives. Among the several approaches targeted toward overall transportation system performance evaluation, one of the more popular and commonly implemented is the measurement of a system's mobility and reliability performance. Industry-wide practice in these areas uses a reference travel time (speed) for calculation of delay, mobility and reliability statistics *(2,3)*. These reference speeds reflect free-flow (unconstrained) travel conditions. In case of uninterrupted facilities (e.g., freeways and Interstates), this refers to travel conditions in which vehicles are not subject to interference from other vehicles and traffic control. For arterial streets, this refers to no interference from other vehicles but includes traffic control delay as defined in this study.

However, the rationale behind the choice of this important parameter is still not entirely established and a few different metrics are adopted in practice. A review of current state-of-practice highlights the different proxies for reference speed used by states and agencies, some of which are based on the posted speed limit (PSL) on a facility. This approach can serve to some extent in situations where recorded travel data are unavailable or inadequate. However, an average driver's perception of reference speed on a roadway segment is influenced not only by the posted limit but also a few other factors including road geometry, driving conditions and presence of traffic signals. Therefore, deriving applicable reference speeds from actual travel time data may be superior to the use of a reference speed value based solely on a fixed PSL. Recorded travel time data can be more reflective of current operational conditions on roadway segments than the PSL.

It is worth recalling at this point that travel time and speed have complimentary relationships in terms of percentiles. For example, the 95th percentile travel time corresponds to the 5th percentile travel speed and vice-versa. Reference speed typically represents unconstrained travel conditions on roadways and its choice on any facility can affect the ability of the corresponding measures to accurately capture actual system performance. Depending on the magnitude of difference in actual and adopted reference values, the reported measures can mis-approximate mobility measures by 20-25% and even higher for reliability measures *(4)*.

This research investigates an appropriate reference time window representative of unconstrained travel conditions by analyzing all-day travel patterns. This was done for both uninterrupted flow facilities (interstates and freeways) and interrupted flow facilities (major and minor urban arterials) because of inherent differences in their travel behavior and characteristics. Using probe-based travel time data from INRIX®, a private-sector data provider, the analysis incorporated different urban areas to provide a more balanced representation of travel patterns and minimize any sampling bias. Researchers also examined a theoretical basis for the choice of a percentile measure for defining reference speed.

BACKGROUND AND LITERATURE REVIEW

Opinions and practice regarding the choice of reference speed vary among states and agencies. While some adopt the PSL on a facility as its reference speed based on the rationale that this is the legal upper limit on how fast drivers can travel on that facility, others prefer to use PSL plus five mph speed as the reference speed. The latter is based on the rationale that during unconstrained hours, when the traffic is light, drivers are free to travel at a speed they feel is reasonable while still remaining within legal bounds. Most travelers tend to drive marginally above the speed limit which allows them to travel slightly faster while still staying within the allowable range not usually ticketed.

Because reference speed is not attainable during several hours of a typical day, some agencies use maximum throughput speeds to calculate mobility measures like area- or state-wide vehicle-hours of delay *(5)*. The maximum throughput speeds are usually between 70%-85% of PSL and are realized when the greatest number of vehicles occupy the highway at a time. Because efficient performance measurement can use rich real-world data, some other agencies prefer to derive reference speeds directly from their available data sets. This removes the potential effects of an arbitrary choice of reference speeds. However, different metrics (e.g., mean- or median-based speed threshold, 75th or 80th percentile speed or maximum throughput speed, etc.) are used for this purpose based on the agency's performance measurement goals. The current research is motivated by the lack of standard practice in this area of performance measurement.

Using a fixed value such as PSL as the reference speed can have some limitations. The reference speed, as perceived by travelers, is influenced by the posted limit combined with a few other factors such as road geometry and driving conditions. For example, travelers may be comfortable traveling faster than the PSL during unconstrained hours on a segment of roadway with standard 12 feet lanes, good sight distances and other favorable travel conditions. But they may travel at a slightly lower speed (closer to the PSL) on segments of the same roadway with less favorable conditions (narrow lanes, lower sight distances, poor visibility, etc.) during the same unconstrained hours. Essentially, different segments of the same roadway with the same PSL may have different reference speeds depending on their geometric and operational characteristics.

Identifying applicable reference speeds for different segments of roadways based on actual travel speed data can be useful. This will enable better reflection of operating conditions on various sections without generalizing conditions over all road sections of a roadway which has been assigned an arbitrary reference value. The National Cooperative Highway Research Program (NCHRP) report 618 recommends evaluating such operational considerations while determining the appropriate reference speed for delay and index computations *(4)*.

Current State-of-the Practice

The choice of reference speed for performance measurement is not uniform among states and agencies in the United States. Different agencies adopt different proxies to assign reference speeds to their facilities as illustrated in Table 1.

TABLE 1 Reference Speed Definitions Adopted by Different Agencies

Agency/Standard	Definition for Reference Speed
Highway Capacity Manual (HCM) *(6)*	• The theoretical speed when the density and flow rate on a study segment are both zero. • The prevailing speed on freeways at flow rates between 0 and 1,000 passenger cars per hour per lane (pc/h/ln). (HCM 2010, pg. 9-8) • In the context of urban streets, reference speed is "…the average running (midblock) speed of through automobiles under low-volume conditions and not delayed by traffic control devices or other vehicles." (HCM 2010, pg. 17-32)
Texas A&M Transportation Institute (TTI) *(7)*	• In line with the HCM definition of *reference speed*, TTI has adopted the term *uncongested speed* in the context of arterial streets to mean the "*…average speed that can be accommodated under relatively low traffic volumes (i.e., no vehicle interactions) on a uniform roadway segment under prevailing roadway and traffic conditions.*" • However, as opposed to the HCM, this definition includes the prevailing traffic signal control delay that occurs in light traffic.
Florida DOT *(8)*	• Field-measured average speed under low volume conditions, when drivers are not constrained by other vehicles, roadway geometry or traffic control. • In absence of field data, reference speed can be estimated at five mph above the posted speed limit.

Some agencies, cities and MPOs adopt the PSL or PSL plus five mph speed as reference speed for their use *(5,7-16)*. Table 2 provides examples to show the current use of different proxies for reference speed in the United States.

TABLE 2 Different Measures of Reference Speed Adopted by U.S. Agencies/ States

Measure used as Reference Speed	State DOT/ MPO
Posted speed limit	Missouri, Nebraska, Nevada, Ohio (defines reference speed as at or near posted limit), Virginia, Wisconsin, Washington
Posted limit plus five	Oregon, Florida
Reference speed*	California, Maryland, Chicago (CMAP)**, New York (NYMTC), Texas

**the term is not specified in a numerical or temporal boundary definition*
***Chicago Metropolitan Agency for Planning (CMAP) measures reference travel speed based on average travel speeds between 8:00 PM and 5:30 AM (15)*

Changes in operational characteristics result in changes in reference speeds on different segments of a roadway with the same PSL. For this reason, adopting a common reference speed may not provide a good representation of the operational characteristics on all segments of the roadway, particularly when there are a large number of segments. When aggregated at an urban area level, this choice of reference can result in significant differences in reported travel performance measures.

METHODOLOGY AND DATA DESCRIPTION

There is a lack of general agreement on what delay measurement intends to report and the benchmark used for it, therefore, this study investigates what the reference speed on a facility is under all favorable conditions. It does not set a threshold for "reasonable expectancy" and defines reference speed accordingly. This will enable more consistency in performance measurement reporting activities as the benchmark is set at an absolute scale and not a relative one defined by the user or agency.

The data for this study come from the INRIX® XD™ database. The XD segments, as denoted by INRIX®, are similar in nature to traffic message channels (TMCs) but typically are shorter and have higher spatial resolution (up to 820 feet [250 meters] on major roads) compared to typical TMC resolutions of 1-3 miles. For the available dataset, these XD segments are typically 1 mile or less in length. The dataset used in this study consists of travel time data for calendar year 2014 from several urban areas in Texas with a few suburban and rural areas also included. The database consists of 10,584 freeway segments and 17,057 arterial segments.

Figure 1 shows the roadways for all four facility types (interstates, freeways, major and minor arterials) used in this study on the state map of Texas.

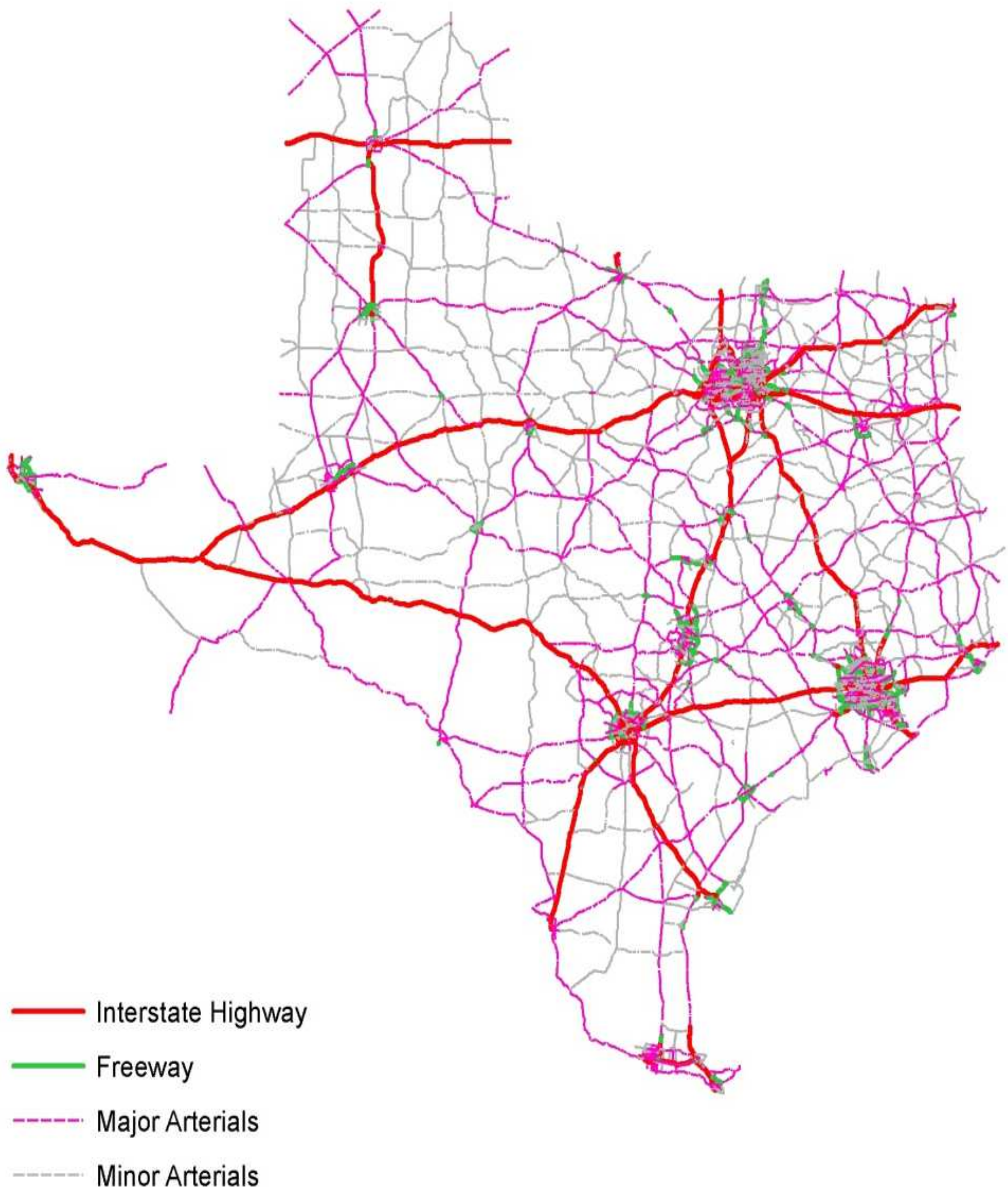


FIGURE 1 Texas state map showing all roadway segments used in the study.

INRIX® provides annual average travel times for each 15-minute interval of each day of the week. For example, a data entry for 01:15 AM on Monday provides the annual average travel time of all vehicles traveling on that segment between 01:15 AM and 01:30 AM. This equates to 672 "cells" of travel time data (4 fifteen-minute intervals per hour*24 hours per day*7 days per week) for each XD segment. The following are some key highlights from initial examination of the data:

- Travel times have been collected using the vehicle probe technique, which captures vehicle travel speeds based on cellular and Global Positioning System (GPS) data.
- The database consists of "point-paired" data which capture the vehicle travel times between points of detection, and not the vehicle spot speeds at individual locations along any road segment. In this respect, these data are representative of space mean speed commonly used in transportation studies.
- The 15-minute aggregated travel times have been converted to respective travel speeds for each segment based on the segment's length. Conversion from travel times to speeds makes understanding the data easier and more intuitive without losing any information.
- Data availability challenges were experienced in some cases. Arterial segments are observed to suffer from lack of data to varying extents during traditional unconstrained hours of the day (9PM-6AM). This is observed particularly for rural arterial segments which witness very sparse traffic during such periods of the day.
- About 23% of all arterial segments (3,923 of 17,057) and 28% of minor arterial segments (1,587 of 5,643) were observed to have less than 50% of data available during usual unconstrained hours (i.e., fewer than 90 of 180 cells filled for the period 9PM-6AM on all weekdays).
- For segments with sparse data (less than 50% availability), an additional time window for unconstrained travel with higher data availability was investigated. Otherwise the corresponding results can be subject to high fluctuation and may not be dependable.

The sequence of data analysis for identification of an unconstrained travel window broadly consists of the following six steps:

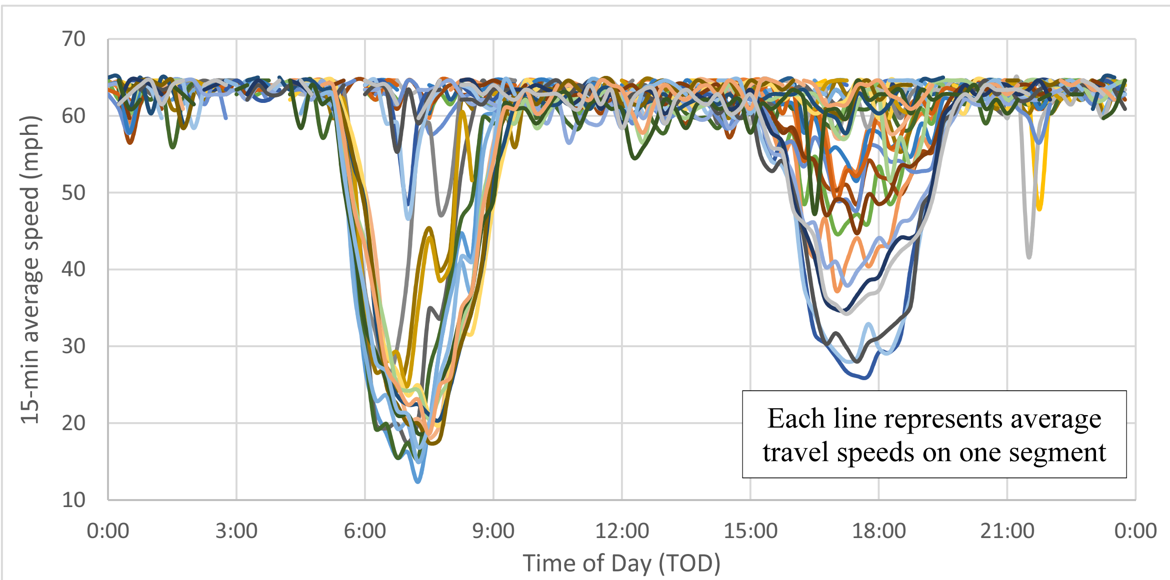
- **Step 1**: Visually inspect all-day 15-minute average travel speed pattern to identify candidate time windows for each class of transportation facility
- **Step 2**: Check for data adequacy within identified time windows
- **Step 3**: Use the coefficient of variation to help identify appropriate time windows and eliminate windows with higher variability in travel speeds
- **Step 4**: Select time window with lower variability if alternate windows have statistically indifferent reference speeds
- **Step 5**: Examine statistical significance of effect of using common time windows for all facility types, and incremental benefit of using weekend travel data in addition to regular workweek travel data
- **Step 6**: Investigate data distribution and choice of appropriate percentile to define reference speed within identified time windows

DATA ANALYSIS AND RESULTS

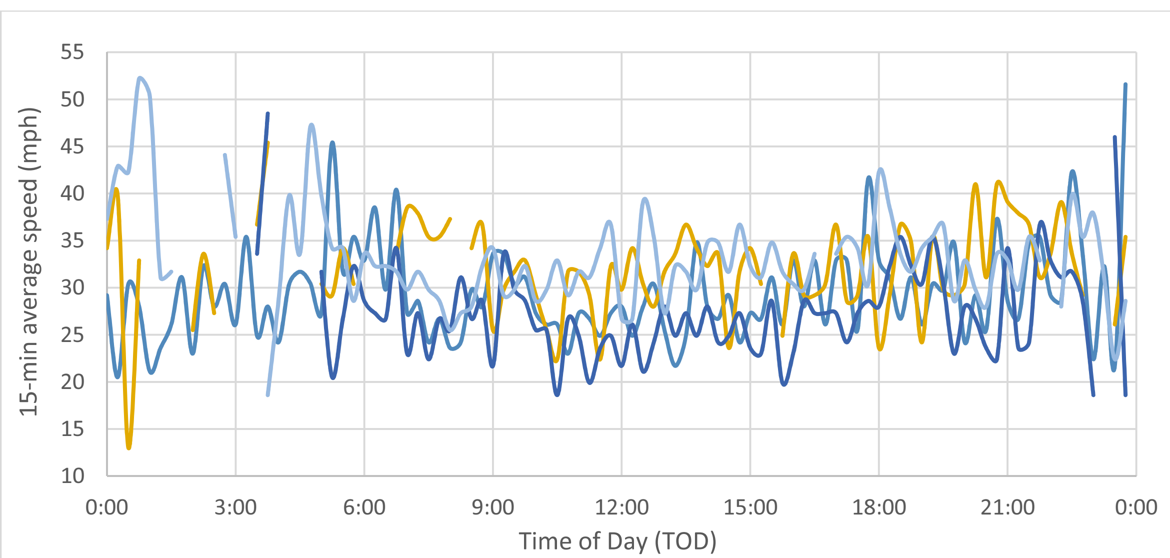
Step 1 and Step 2: Visual Inspection of All-Day Travel Patterns and Check for Data Adequacy

The preliminary step in narrowing candidate travel windows with speeds potentially close to the facility's reference speed is visually inspecting travel speed patterns for all-day travel. This gives an estimate of smaller temporal windows that can be investigated further. This exercise was performed for all uninterrupted and interrupted flow facilities included in this study. Figure 2(a) and Figure 2(b) show typical all-day travel speed patterns for a few freeway and arterial street facilities respectively. Each line represents annual average 15-minute travel speeds throughout the day on one segment. It should be noted that the speed patterns shown are line graphs instead of point scatter plots just for ease of observation. It is understood that because of 15-minute aggregation, the data are not continuous in the true sense, which the line graphs may suggest.

As shown in Figure 2(a), freeway facilities tend to show significantly lower speeds with onset of peak period congestion during morning and evening peaks. Although speeds tend to decrease for interrupted flow facilities also, the magnitude of drop in speed during peak periods is smaller. Figure 2(b) also shows that some arterial street segments lacked travel time data during overnight period.



(a) Travel speed variation by time of day for freeway facilities.



(b) Travel speed variation by time of day for arterial street facilities.

FIGURE 2 Travel speed variation on uninterrupted and interrupted flow facilities.

Visual inspection led to a few candidate time windows of unconstrained travel for consideration. Table 3 provides details on average data availability for different facility types during two such unconstrained travel windows. This data availability is expressed in terms of the average percentage of cells filled out of 180 cells (for 9PM-6AM) or 120 cells (for 11PM-5AM).

TABLE 3 Average Percentage Data Availability for Different Facility Types during Unconstrained Travel Windows

Facility Type		Percentage Data Availability Within Specified Time Window	
		11 PM – 5 AM	9 PM – 6 AM
Uninterrupted Flow	Interstate	91.8	96.2
	Freeway	79.5	86.9
Interrupted Flow	Major Arterial	66.1	78.1
	Minor Arterial	56.8	65.2

Even within an expanded window of 9PM-6AM, a proportion of arterial streets did not have sufficient data to draw useful inferences. In particular, about 28% of minor arterial segments (1,587 of 5,643) had less than 50% of 180 cells of data filled for the period 9PM-6AM.

For such facilities, an additional mid-day time window was required because conclusions based on very sparse data can be subject to high fluctuations and may not be dependable for sustained performance measurement. This time window was determined to be 11AM-4PM for which the next section provides more details in terms of data availability and variability within the time window.

Step 3 and Step 4: Determination of Appropriate Time Windows and Selection between Candidate Windows

Travel speeds can achieve high values during different parts of the day, however, it is difficult and impractical to assign several distinct and spaced out travel time windows as reference speed time windows. Also, although a relatively high average speed may be observed during a few 15-minute windows in a short period of time, it is not very meaningful to consider such spikes in speeds if these speeds cannot be maintained over a longer interval of time. Therefore, a balance between the magnitude of average 15-minute travel speeds and their consistency over a reasonable duration is necessary.

As a result, the all-day travel patterns were observed in conjunction with the coefficient of variation of average travel speeds. The coefficient of variation, CV, is the ratio of standard deviation (σ) and the mean (μ).

$$CV = \frac{\sigma}{\mu}$$

Mean and standard deviation of travel speed were calculated on each segment for different periods of the day. For example, if the mean speed was calculated on a segment for the duration 6AM-10AM on all weekdays (average of 80 cell values [4 fifteen-min intervals per hour*4 hours*5 weekdays]), the standard deviation of speeds for the same time period was also computed to obtain the CV for the time period. The following are a few key highlights of this step of analysis:

- The coefficient of variation of travel speed was calculated using values for standard deviation and mean for all time windows resulting from step 1. Time periods with CV greater than 10% were not considered further.
- Unconstrained travel time windows with high values of mean and 85th percentile speeds were investigated among time windows with CV ≤ 10%. As shown in Table 4, these time windows are slightly different depending on the type of transportation facility.

TABLE 4 Unconstrained Travel Windows for Different Facility Types

Facility Type		Candidate Time Windows for Unconstrained Travel	
		Daytime Window(s)	Nighttime Window(s)
Uninterrupted Flow	Interstate and Freeway	9 AM-11 AM, 1 PM-3 PM	7 PM-9 PM, 10 PM-6 AM, 2 AM-5 AM
Interrupted Flow	Major Arterial	10 AM-1 PM, 2 PM-4 PM	9 PM-6 AM
	Minor Arterial	8 AM-10 AM, 11 AM-4 PM	10 AM-12 AM, 2 AM-6 AM

CV was preferred as a metric over standard deviation because it normalizes the variability in speeds with respect to the mean speed. For example, while a freeway facility can have a reference speed of 60 mph, an arterial facility can have it as 40 mph, and CV is able to account for these different levels of base speeds better than a fixed value of standard deviation. Considering all roadway segments, the mean CV was found to be 5% for uninterrupted flow facilities during the chosen reference travel time window (9PM-6AM), while it was 8% for interrupted flow facilities.

Step 5: Check for Statistical Effect of Use of Alternate Time Windows

Use of Weekend Travel Data Along With Weekday Travel Data

There is no common standard among agencies for use of weekend travel data. Following the same procedure (calculating mean and standard deviation to get CV and limiting CV to a maximum value of 10%), the reference travel time window during weekends (Saturday and Sunday) was identified as 5AM-9AM. This time period was found to be consistent with current practice of several agencies which use weekend data to define reference speed *(13)*. The following are a few key observations for this step of analysis:

- For 16,225 of 17,057 arterial segments and for 9,686 of 10,584 freeway segments, including the weekend unconstrained travel (5AM-9AM) did not have a statistically significant effect on reference speeds.
- For the small portion of segments that showed numerical increase in values of reference speeds when weekend data were included, the highest magnitude of increase compared to "weekday-only" data was 1.7 mph and most of them ranged between no increase to an increase of 1 mph.

This shows that for most transportation facilities, as long as the reference travel time windows are chosen appropriately, the reference speed does not change significantly when weekend travel data are included. This is intuitive because travel behavior for a driver familiar with the facility should not change significantly during what are typically low traffic periods when traffic pressure does not affect driving behavior.

Arterial Street Type (Major vs. Minor) Effect on Unconstrained Travel Window

The travel time pattern is different for major and minor arterials. Figure 3 shows the variation of average 15-minute travel speed throughout a day for major and minor arterial street segments separately. Each data point is the average travel speed for all major arterial segments (solid line) or minor arterial segments (dotted line) for each 15-minute period.

The average travel speeds on all major arterial segments follow a pattern similar to freeways, wherein the overnight period travel speeds are higher than the rest of the day. However, minor arterial streets follow a slightly different pattern wherein the nighttime travel speeds are lower than some parts of daytime travel and there is higher variability of average speeds within the overnight time window. This typically happens because traffic on major arterial streets is given priority over minor street traffic during overnight period. For example, if the signals are actuated, the minor street does not receive a green indication until a vehicular call is placed through detection. Even when the signals are pre-timed, the major street receives most of the green phase, and therefore, minor street vehicles are delayed although there is light traffic on minor streets. Minor street vehicles which are fortunate to arrive at the signal when it is green register lower travel times (higher average speeds), while those which need to wait for the green indication experience a higher travel time. This gives rise to an overall higher fluctuation in travel time as seen in the left portion of the graph (12AM-6AM) for minor arterial segments.

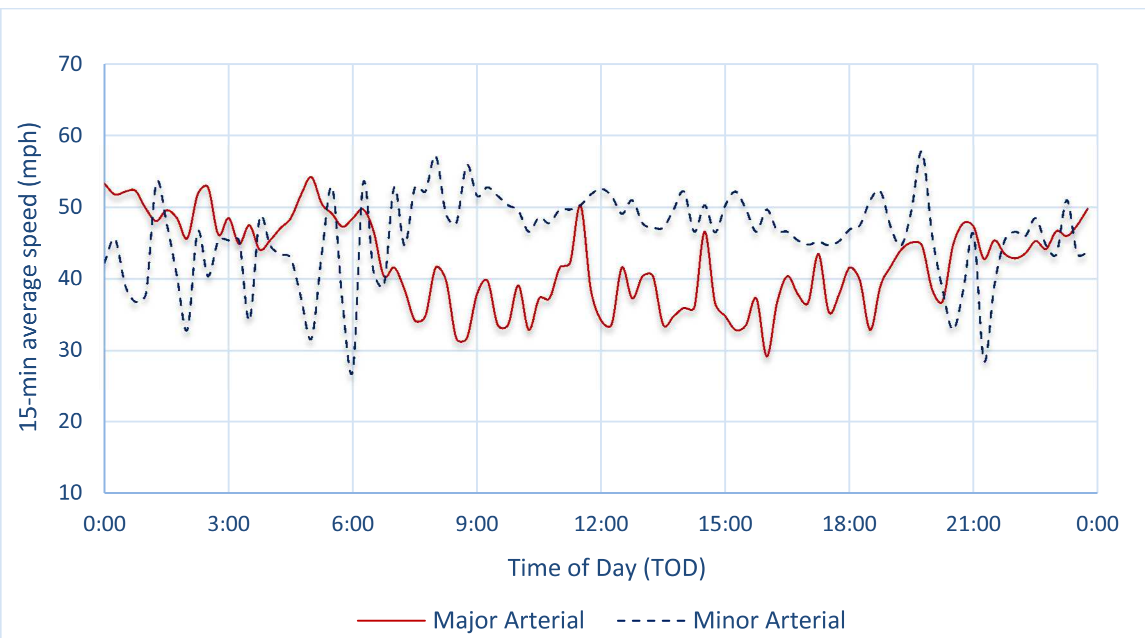


FIGURE 3 Travel speed variation on major and minor arterial street facilities.

Use of a Common Time Window for All Facility Types

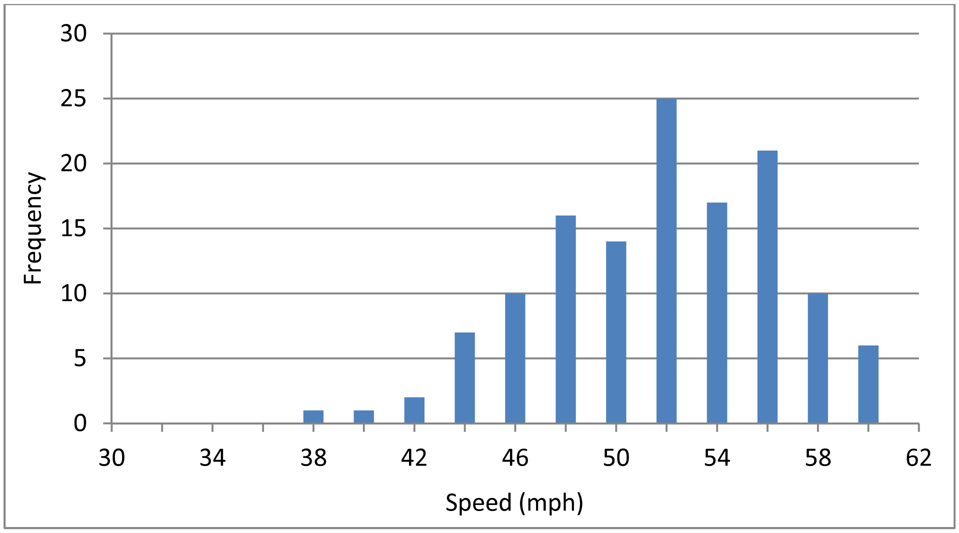
Data adequacy can be a challenge during nighttime hours. As seen in Table 3, to improve average data availability for arterial segments, the reference travel window was expanded from 11PM-5AM to 9PM-6AM. The following are a few key observations regarding this expansion:

- It was found that for 9,529 of 10,584 freeway segments, changing from the 11PM-5AM window to 9PM-6AM window does not have a statistically significant effect on reference speeds.
- For the remaining segments in which the speed differences were found to be significant, the maximum magnitude of difference was 1.8 mph. This can have an effect on delay and mobility metrics depending on the length of the segment and the volume of traffic on it. This aspect is not explored in this research and can be studied further.
- Considering all segments irrespective of facility type, it is found that the average value of CV remains below 10% when the data availability for the 9PM-6AM period is at least 50% (i.e., at least 90 of 180 cells are filled). When the data availability falls below 50% the average CV stays above 12%.
- For facilities which have less than 50% data within the traditional nighttime period (9PM-6AM), nighttime data can be supplemented with mid-day data (11AM-4PM) to derive a more consistent (less variable) reference speed.

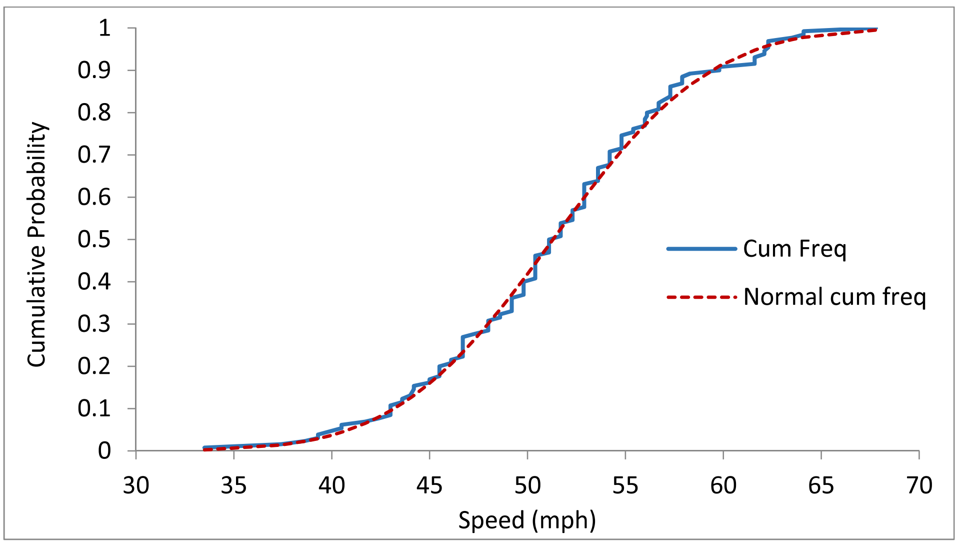
Step 6: Data Distribution and Selection of Appropriate Percentile to Define Reference Speed

A vast majority of transportation data, particularly traffic speed data, start approaching a normal distribution as the level of data aggregation increases. With increasing aggregation, the travel time data start to move from a right skew (a longer right tail) to a more symmetric normal distribution. Also, the travel speed distribution moves from a left skew distribution to a normal distribution. This is experienced even more during unconstrained travel windows when vehicles travel at similar speeds and the variability is limited. A few assumptions regularly used in transportation engineering are based on normal distribution of data. For example, the basis behind using the 85th percentile value to assign speed limit on roadways is that the 85th percentile captures data within two standard deviations of the mean (and the median if the data is perfectly normal). A few other related concepts are discussed in more detail in this section.

Two of the more popular methods to check for normality of data are the histogram and the cumulative distribution function plot (CDF plot). The 15-minute average speed data from preferred unconstrained travel time windows (9PM-6AM for freeways and major arterial streets; plus 11AM-4PM for minor arterial streets) were used to obtain their histogram and CDF plots. As shown in Figure 4, the results indicate that within the chosen reference travel windows, the data follow a normal distribution very closely. The corresponding cumulative distribution function plot is shown in Figure 4(b). The quantiles obtained from the INRIX® speed data are plotted along with the standard normal distribution quantiles, thus providing a side-by-side comparison to check for normality of data. The dashed line signifies normal distribution quantiles and the solid line represents quantiles for the INRIX® speed data.



(a) Histogram of average speeds on a freeway segment (9PM-6AM, Mon-Fri).



(b) CDF plot of average speeds on a freeway segment (9PM-6AM, Mon-Fri).

FIGURE 4 Histogram and CDF plot of average speeds on uninterrupted flow facilities.

A chi-square test was performed to check for goodness of fit to a normal distribution. Major arterial streets showed the highest conformity to a normal distribution (10,161 of 10,927 segments [93%]) followed by uninterrupted flow facilities (91%), while approximately 68% of minor arterial segments (4,167 of 6,130) were found to follow the normal distribution. Travel speed data on most facility types follow a normal distribution during unconstrained travel time windows. The data for minor arterials show a slight left skew which indicates that there is a relatively higher proportion of slower speeds on minor arterials compared to other facility types. One of the reasons for this observation can be that the reference time window for minor arterials consists of a daytime window also, and therefore can witness some slower speeds relative to traditional nighttime hours for the other two facility types. Moreover, compared to the major street, a higher portion of vehicles on the minor street is likely to witness red signal on arrival, thereby reducing the average travel speed.

The literature *(17,18)* suggests that the reasons for choosing the 85th percentile for defining reference speed on transportation facilities include:

i. The gradient (slope) of the cumulative distribution curve changes at this percentile value. The gradient at or below this point is relatively sharp, while it becomes more gentle after this point.
ii. 15% of travelers are considered to be a fair number traveling in a more favorable/uncongested condition.
iii. The 85th percentile value approximates mean speed plus one standard deviation of speeds if they are normally distributed, and thus includes 68% of the total data.

Another important rationale behind adopting the 85th percentile for defining reference speed in this study is that the data used are 15-minute aggregated averages. This aggregation process removes most of the driver-to-driver variation and the effects of very high individual speeds are minimized. The distribution of 15-minute average speeds indicates that groups of drivers (platoons of vehicles) are making different decisions in actuation and priority treatment scenarios as discussed in earlier sections. Because this analysis focuses on speeds that represent unconstrained conditions, and it is difficult to know from aggregated speeds why drivers are making different driving decisions, a higher percentile is a better reflection of "actual unconstrained" conditions. Moreover, the point of inflection (gradient change) seems to lie close to the 85th percentile for the INRIX® travel speed database as well [see Figure 4(b)]. Basing the percentile choice on the phenomenon of gradient change at that specific percentile seems rational. It suggests that the rate at which more people traveling at increasing speeds are being added to the sample remains constant until this percentile value, after which that rate drops, meaning these faster motorists are getting added at a slower rate.

Another option would be to use the mean travel speed (or 50th percentile travel speed for normal distribution) during unconstrained conditions as the reference speed. Therefore researchers also examined the difference between the 85th percentile and the 50th percentile speed during unconstrained travel conditions. The two speeds were nearly identical and thus the 85th percentile was used based on the theoretical background discussed above.

RECOMMENDATIONS

Depending on the level of data availability, this research suggests use of one among two alternate time windows of unconstrained travel identified based on all-day travel patterns. The primary window is 9PM-6AM on weekdays for all segments which have at least 50% data availability within this time period. Considering 15-minute data aggregation, this equates to at least 90 cells filled out of 180. For facilities with lower data availability, this time window should be supplemented with mid-day (11AM-4PM) data which can help lower the variability of travel speed compared to nighttime data alone. Weekend travel data did not significantly impact reference speed, therefore, it is recommended to not include it in analysis while determining reference speed to reduce computational requirements and complexity.

The 85th percentile value of aggregated travel speeds is a reasonable measure of reference speed which can be used for performance measurement activities. A snapshot of the key recommendations is provided in Table 5.

TABLE 5 Key Recommendations of the Study

Data Availability during 9PM-6AM Time Window	Recommended Reference Travel Time Window	Recommended Reference Speed Percentile	Notes
≥ 50 percent	9 PM – 6 AM weekdays (Mon-Fri)	85^{th} percentile of average speeds within chosen time window	Consistent, less variable data; conformity to normal distribution
< 50 percent	9 PM – 6 AM weekdays (Mon-Fri) + 11 AM – 4 PM weekdays (Mon-Fri)		Left skew in speed distribution; low data availability and high variability during nighttime period

Note: For more detailed information based on facility type, refer to "Determining Reference Speed from Probe-Based Travel Speed Data," K. Jha, Master's Thesis, Texas A&M University (19)

CONCLUSIONS

The reference speed represents unconstrained travel conditions on transportation facilities and can be measured during daily temporal windows when the driver has a choice of travel speed unimpeded by other travelers. The purpose of this study is to provide a basis for benchmarking reference speed on transportation facilities for use in mobility and reliability performance measures.

Use of PSL or PSL+5 as reference speed has advantages of being easy to obtain and stable. However, a reference speed based on actual travel time (speed) data instead of a fixed reference (such as the PSL) has advantages of being adaptive, updateable (on a periodic basis) and a closer representation of prevailing operational conditions and driver experience. This also does away with the need for inventory data (for PSL) in addition to a speed database. Based on this study, the 85^{th} percentile of average 15-minute speeds during 9PM-6AM is recommended as the reference travel speed when data availability for this period is at least 50%. For lower data availability, this data should be supplemented with midday travel data during 11AM-4PM. On minor arterial streets, the 85^{th} percentile of supplemented data (nighttime and mid-day) is more representative of reference travel conditions.

As more robust and granular datasets become available, further study can examine the sensitivity of derived reference speeds to level of data disaggregation. Parameters such as the coefficient of variation may need to be adjusted accordingly (e.g., lower data aggregation may warrant higher CV). It can be expected that more granular data (low degree of data aggregation) can provide more insights into all-day travel patterns. However, care should be exercised while making tradeoffs between data interpretability, ease-of-analysis and associated marginal information. As discussed earlier, several distantly spaced out time windows of unconstrained travel throughout the day may be informative in terms of unconstrained travel but such an approach may not be practically applicable or useful. The balance between adequacy of data and its variability within identified time windows should be considered while conducting performance measurement analyses. The recommended approach can also aid in improving the ability to conduct system performance evaluation with just the travel time database, without requiring additional information about facility type. This can make the exercise more efficient and implementable in the long run.

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