

## Selection of an Appropriate Reference Speed for the Calculation of Highway Performance Measures

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**FINAL REPORT**

**SELECTION OF AN APPROPRIATE REFERENCE SPEED FOR THE  
CALCULATION OF HIGHWAY PERFORMANCE MEASURES**

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## ABSTRACT

This study examines the impact of various reference speed estimation methods on interstate highway performance measures, alongside an exploration of factors influencing reference speed on arterials. Using probe speed data from the National Performance Management Research Data Set and INRIX, Inc., datasets, several reference speed estimation methods are evaluated to assess how these different estimates affect key performance metrics, including travel delay and the Planning Time Index. Findings indicate that reference speeds derived from the 85th-percentile speed during low-traffic-volume periods are consistent across methods and provide reliable measurement for delay and Planning Time Index calculations. In addition to interstate analysis, the study assesses the probe data quality on arterial networks, investigating factors such as segment length and traffic signal density to understand their impacts on arterial reference speed. Results suggest that although reference speed estimation methods are well established for interstates, estimating reference speed on arterials requires further investigation and exploration due to inherent variability. This study recommends that the Traffic Operations Division of the Virginia Department of Transportation adopt the 85th-percentile-based reference speed calculation method as a best practice for interstate performance measurement purposes. This study also recommends further research to develop a reference speed estimation method for arterial performance measures. Implementing these recommendations would help improve the consistency of performance measurement, thus enhancing support for data-driven policy decisions.

## **FINAL REPORT**

### **SELECTION OF AN APPROPRIATE REFERENCE SPEED FOR THE CALCULATION OF HIGHWAY PERFORMANCE MEASURES**

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## **INTRODUCTION**

Transportation agencies increasingly adopt performance management principles to make investment and policy decisions (FHWA, 2024). Using data from a variety of sources, performance measures are developed to establish performance targets and track progress toward achieving the targets. Mobility and reliability performance measures, such as travel delay and the Planning Time Index (PTI), are commonly used in performance-based planning and programming. Calculating these performance measures requires a predefined baseline, which is established using a reference speed selected by the user (Jha, 2017; Margiotta et al., 2015). Reference speed represents the average speed in uncongested or free-flow traffic conditions. Free flow is a condition where traffic flow is unaffected by upstream or downstream conditions, and the speed at which free-flow traffic prevails is called free-flow speed (TRB, 2022). The ideal way to determine free-flow speed is to measure it in the field through a speed study in low-volume conditions on the facility or a comparable facility if the facility is in the planning stage (Dowling et al., 2016). However, field studies can be expensive and unfeasible for screening analysis or a large number of study sites. Various methods have been developed to estimate free-flow speed, ranging from “rule of thumb” estimate (e.g., posted speed limit [PSL] plus 5 miles per hour [mph]) to complex statistical and machine learning models.

The term “reference speed” is defined to avoid confusion, as free-flow speed may have a very specific definition, such as those definitions used in highway capacity analyses (Margiotta et al., 2015).

Reference speed is used in the context of performance measures. Free-flow speed is often used as reference speed in the literature, but it is also common for agencies to opt for alternatives to set a benchmark for a desirable or achievable condition.

The use of a specifically defined reference speed provides a consistent method for calculating mobility and travel time reliability measures across different studies and areas. Selecting an appropriate reference speed is crucial for accurate and comparable performance measures because the selection could affect the ability of the computed mobility and reliability measures to reflect the actual highway system performance (Cambridge Systematics, Inc. et al., 2008; Jha, 2017). Differences in reference speed estimation methods can lead to variations in the values of reference speed, which may impact the performance measures derived from them and

thus influence the decision-making outcomes based on the calculated measures. However, how the selection of reference speed can affect the calculated mobility and reliability measures has not been extensively studied, and guidelines are lacking for choosing an appropriate reference speed for highway performance measurement.

This study compares reference speeds calculated with different methods and explores the impact of their differences on mobility and reliability performance measures. In addition, this study explores the influence of congestion thresholds on estimated delay outcomes. Particular attention is given to the implications of how different approaches can affect decision-making processes in benefit analysis and project prioritization.

## **PURPOSE AND SCOPE**

The purposes of this study are to (1) compare commonly used reference speeds representative of free-flow conditions for interstate highways, (2) evaluate how the selection of reference speed affects the performance measures that are calculated using this value, and (3) explore the factors affecting reference speed for arterial roads using probe vehicle data.

The reference speed methods studied are intended for systemwide performance management. This study uses data for all National Highway System roads maintained by the Virginia Department of Transportation (VDOT). The performance measures studied are limited to mobility and reliability measures for interstate highways.

## **METHODOLOGY**

The following tasks were conducted to achieve the study objectives.

1. Literature review.
2. Data collection and preparation.
3. Comparison of reference speed methods for interstate highways.
4. Comparison of performance measures for interstate highways.
5. Exploration of factors affecting reference speed on arterials.

### **Literature Review**

A comprehensive literature review was conducted to examine various aspects of reference speed estimation and its impact on highway system performance measures. The topics reviewed included methods to determine reference speed or travel time, which serve as baseline for calculating performance indicators. The review also explored the prevalent practices in selecting reference speeds across different transportation agencies. Furthermore, the literature review aimed to identify studies that analyzed how the choice of reference speed influences the accuracy and interpretation of mobility and reliability measures, and the sensitivity of these metrics to the selected baseline condition.

In addition to reference speed, a review of congestion thresholds was conducted, a concept used to determine whether a congestion condition exists for delay calculations. This concept is critical in understanding the point at which traffic flow transitions from acceptable to congested conditions, thereby affecting delay and other related performance measures.

The extensive search of published materials also identified various performance measures that are calculated relative to travel times under uncongested or free-flow conditions. These findings provide insight into the common approaches and best practices for assessing highway system mobility and reliability, providing a foundation for more accurate and consistent measures for various performance measurement activities.

### **Data Collection and Preparation**

Data collected for this study included probe speed data, traffic incidents, traffic volume, and roadway inventory data. Probe speeds from January 2019 to December 2023 were obtained from two datasets: the National Performance Management Research Data Set (NPMRDS) and a dataset from third-party probe data vendor INRIX, Inc. The 15-minute average speeds were collected from both NPMRDS and INRIX for each Traffic Message Channel (TMC) segment on the National Highway System routes maintained by VDOT, along with the length and location of each TMC segment. Traffic volumes, incidents, and roadway inventory data in the study period were provided by VDOT. The roadway inventory data included the number of through lanes, PSL, locations of traffic signals, and urban/rural designation.

### **Spatial Units and Data Aggregation**

The TMC segment served as the primary spatial unit for this study. Speed and volume data were aggregated at 15-minute intervals for each TMC segment to maintain temporal consistency across datasets. Based on the start and end times and locations of traffic incidents, the presence of traffic incidents was identified for each analysis time interval and each segment. The roadway inventory data, provided in geographic information system format, was processed using ArcGIS to associate each TMC segment with its respective roadway attributes. Quality checks were performed to ensure the accuracy, completeness, and relevance of all variables.

### **Data Alignment Across Datasets and Years**

To enable a consistent comparison between the NPMRDS and INRIX dataset, TMC segments were aligned by matching their TMC identifications and start and end locations. Although the INRIX and NPMRDS TMC networks are similar, they are not always identical, which necessitated careful cross-referencing to achieve consistent alignment. In addition, TMC definitions can vary across years, with segments being added or removed in both datasets. To maintain continuity, only TMCs that were present across all study years were included, resulting in a standardized set of 7,140 TMCs covering approximately 8,414 directional miles of National Highway System routes in Virginia. Within this standardized set, the interstate network consists of 1,959 TMCs covering 2,292 miles, and the arterial network consists of 5,181 TMCs covering 6,122 miles.

## **Data Quality and Availability**

NPMRDS data points are based on observed values, whereas INRIX data points are imputed data, and each data point is assigned a confidence score. For INRIX, a score of 30 indicates real-time data, although these speed values are generated by algorithms and do not necessarily represent direct readings from the field (RITIS, 2024). For 15-minute aggregated INRIX data, the score is the average of the 15 underlying 1-minute scores. A 15-minute score of 30 means all 15 underlying 1-minute data points have a score of 30, suggesting all real-time data. Conversely, a score of 20 indicates that all 15 underlying data points are historical values. Scores between 20 and 30 represent a mixture of real-time and historical data.

Data density in the NPMRDS is determined by the number of readings per 15-minute reporting interval. Intervals with fewer than five readings are labeled as A, intervals with five to nine readings as B, and intervals with more than nine readings as C (RITIS, 2024).

Data availability is crucial in estimating any measurements using probe datasets, as it directly impacts the accuracy and reliability of the analysis. Existing literature shows that probe data availability is generally high on interstates but notably lower on arterial networks (Vander Laan and Zahedian, 2021). However, the exact extent of this limitation on arterial networks is not well documented. Data availability is assessed through a sensitivity analysis by adjusting the confidence score threshold for INRIX and the data density threshold for NPMRDS. This approach examines the percentage of timestamps that meet each threshold level, providing information on the data coverage under varying quality criteria.

### **Comparison of Reference Speed Methods for Interstates**

Transportation agencies and researchers have developed various methods to estimate reference speed for calculating highway mobility and reliability measures. Some methods are easy to use, whereas others may involve significant efforts (e.g., data preparation). This study identifies and compares several widely used methods in the literature, including methods based on the percentile of speed and those based on the PSL. The similarities and differences among the methods were analyzed. Comparisons were performed for different segment groups with varying traffic, roadway geometry, and environmental characteristics. The differences between estimated reference speed and PSL were also evaluated. The goals were to understand how these different methods for calculating reference speed compare with each other and how to select appropriate reference speed for performance measurement.

### **Comparison of Performance Measures for Interstates**

Understanding the differences among reference speed estimation methods and how the differences can affect estimated performance outcomes is important in selecting the appropriate reference speed. This study focused on analyzing how the differences between reference speed calculation methods affect mobility and reliability performance measures. The mobility measure analyzed in this study was the travel delay, which is the most widely used mobility metric for transportation planning and management. The travel time reliability measure considered was PTI, which has gained prominence because of its straightforward interpretation and

practicability. PTI is a ratio of the 95th-percentile travel time to the free-flow travel time, and it represents the total time that should be planned to arrive on time for 95% of all trips. A higher PTI value means more variance in travel time from day to day or across different times of the day and, thus, is less reliable.

Free-flow travel time is a foundational component for calculating delay and PTI on interstates. Free-flow travel time can be calculated using reference speed and TMC segment length. This study evaluated several reference speed methods by comparing the variabilities between methods and across different years; the impacts of their differences on the values and ranking of delay and PTI were also evaluated.

Analyses were conducted at the statewide, district, and corridor levels to compare delays estimated based on different congestion thresholds. For PTI, the 95th-percentile speeds and PTI of the following periods were calculated.

- Weekday a.m. peak: 6 a.m. to 10 p.m.
- Weekday p.m. peak: 4 p.m. to 8 p.m.
- Weekday mid-day: 10 a.m. to 4 p.m.
- Weekend: 6 a.m. to 8 p.m.

The results from each reference speed method were then visualized and compared.

### **Exploration of Factors Affecting Reference Speed on Arterials**

Arterial traffic is considerably more complex than that on interstates because of varying traffic control and roadway attributes (e.g., traffic signals, closely spaced intersections, driveways, turn lanes). Moreover, data availability on arterials is usually worse than that on interstates, especially on low-volume roads. This study evaluated the availability of probe speeds on non-interstate National Highway System routes to assess the potential of estimating reference speeds for those roads using the probe dataset. The cumulative distribution functions of traffic speeds were generated for each TMC segment, and reference speeds calculated by several methods were compared.

## **RESULTS AND DISCUSSION**

### **Literature Review**

#### **Free-Flow Speed**

Free-flow speed is a key parameter to calculate various other traffic parameters, such as capacity and level of service. The Highway Capacity Manual (HCM) defines free-flow speed as the average speed of vehicles on a given segment, measured under low-volume conditions when drivers are free to drive at their desired speed and are not constrained by the presence of other vehicles or downstream traffic control devices (TRB, 2022). In HCM, free-flow speed is the prevailing speed on freeways at flow rates between 0 and 1,000 passenger cars per hour per lane.

This definition has been adopted in the VDOT Traffic Operations and Safety Analysis Manual (VDOT, 2020). For urban streets, HCM defines free-flow speed as the average midblock running speed under low-volume conditions not influenced by traffic control devices or other vehicles. National Cooperative Highway Research Program Report 618 defines free-flow speed as the average speed that can be accommodated under relatively low traffic volumes on a uniform roadway segment under prevailing roadway and traffic conditions (Cambridge Systematics, Inc. et al., 2008).

Free-flow traffic conditions are typically experienced during off-peak hours, with the early morning hours providing the most favorable situation (TRB, 2022). Measuring it directly in the field in low-volume conditions is the most accurate method to determine free-flow speed. However, determining true free-flow speed may be difficult to do given data constraints, so the value of free-flow speed is estimated using algorithms when individual vehicle-level data are unavailable. A common approach to estimating free-flow speed is to use the 85th-percentile speed in the off-peak period, ideally using continuous measured speed data for at least 1 year (Cambridge Systematics, Inc. et al., 2008).

Free-flow speed, as defined in the HCM, can be used as a reference speed to calculate delay and travel time reliability measures (Margiotta et al., 2015). In this case, the baseline from which to calculate performance measures is drivers' desired speed. However, transportation agencies often adopt another value of reference speed more suitable for a particular analysis. By tailoring the reference speed to fit the purpose of the analysis, agencies can enhance the effectiveness of their assessments.

## **Reference Speed**

Transportation agencies increasingly focus on performance-based planning and programming, making it critical to develop effective performance measures. Delay and reliability measures are of high interest to agencies. A key step in computing these measures is to establish a benchmark for comparison using a reference speed. Reference speed represents the average speed in uncongested or free-flow travel conditions. It should be determined for each study segment individually (Margiotta et al., 2015). The reference speed adopted to calculate mobility and reliability performance measures varies among transportation agencies. The literature does not agree on a single optimal reference speed for calculating mobility and travel time reliability measures. Also, having one reference speed for all performance measurement activities is not reasonable because the selection can be influenced by a variety of factors, such as the specific goals of the analysis, the intended audience, and the context in which the performance measures will be used. For instance, a lower reference speed representing an achievable condition, instead of free-flow speed, may be used to calculate the performance measures of a proposed urban congestion mediation project with limited funding.

Various methodologies have been developed to establish reference speed. Agencies widely use the following reference speeds:

- PSL or PSL plus 5 or 10 mph: PSLs are readily available for agencies. However, for communicating with the public, it could be challenging to interpret delay and reliability

measures calculated using travel time at the PSL as a benchmark because reference speeds higher than the PSL may create the perception of speeding (Cambridge Systematics, Inc. et al., 2008).

- The mean or percentile of the speeds in low-volume conditions: This is the most common method to estimate reference speed, with the 85th percentile of average segment speeds in low-volume conditions as a popular option (Margiotta et al., 2015).
- For urban arterials, the method includes the traffic control delay in low-volume conditions, which is different from the free-flow speed method in the HCM. The low-volume conditions can be defined by a time window (e.g., nighttime from 10 p.m. to 5 a.m.) or traffic volume (e.g., volume less than 700 vehicles per hour). Different time windows and volume levels are used in the literature. The 85th percentile of average segment speeds during nighttime hours is widely used (Margiotta et al., 2015). The Urban Congestion Report uses the 85th-percentile speed on weekdays (9 a.m.–4 p.m., 7 p.m.–10 p.m.) and weekends (6 a.m.–10 p.m.) to calculate reference speed (FHWA, 2020). Zhang and Chen (2015) suggested the 85th-percentile speed from 6 a.m. to 8 p.m. for urban arterials. Jha (2017) found that the 85th-percentile speeds during the time windows of 9 p.m. to 6 a.m. on weekdays for freeways and principal arterials and 11 a.m. to 4 p.m. on minor arterials produced reasonable reference speeds for calculating mobility and reliability measures. This method requires an adequate amount of field data from continuous sources for the off-peak period selected. If no enough field data are available, PSL plus 5 mph is recommended because this estimate provides a reasonable approximation to field data-derived reference speed (Margiotta et al., 2015).
- Reference speed provided by the data vendor: Some probe data providers offer a reference speed on segment together with speed and travel time observations, which approximates free-flow speed. For example, the NPMRDS reference speed is the 85th percentile of the speeds between 10 p.m. and 5 a.m., and from 2013, this reference speed is calculated using data from March 1 to May 31 of the most recent NPMRDS map year (RITIS, 2024). The reference speed in INRIX datasets is the 66th-percentile speed on a segment for all time periods (RITIS, 2024). Directly using the reference speeds provided by a data vendor to calculate performance measures eliminates the need for additional calculations.

## Measures of Travel Time Reliability and Delay

Travel time reliability measures are often calculated relative to free-flow travel time, which is the travel time on a segment that occurs when vehicles travel at free-flow speed (Texas A&M Transportation Institute, 2023; TRB, 2022). The reliability measures widely used by agencies include:

$$\text{Planning Time Index: } PTI = \frac{95th \text{ Percentile Travel Time}}{Free-Flow Travel Time}$$

$$\text{Mean Travel Time Index (TTI): } TTI_{mean} = \frac{Mean Travel Time}{Free-Flow Travel Time}$$

$$\text{80th Percentile Travel Time Index: } TTI_{80} = \frac{80th \text{ Percentile Travel Time}}{Free-Flow Travel Time}$$

$$\text{50th Percentile Travel Time Index: } TTI_{50} = \frac{50th \text{ Percentile Travel Time}}{Free-Flow Travel Time}$$

Semi-Standard Deviation:

$$\sqrt{\frac{1}{n} \times \sum_{i=1}^n (\text{Free-Flow Travel Time} - \text{Observed Travel Time})^2}$$

n = the total number of observations below free-flow speed

$$\text{Misery Index: } \frac{\text{Average of the highest 5 percent of travel times}}{\text{Free-Flow Travel Time}}$$

$$\text{Commuter Stress Index: } \frac{\text{Average Travel Time During Peak Period in Peak Travel Direction}}{\text{Free-Flow Travel Time}}$$

For measuring mobility, vehicle-hours of delay is the primary metric used for monitoring and reporting performance at the segment level. It is calculated by multiplying traffic volume by the extra travel time caused by congestion. To calculate delay, a threshold speed is set as a reference point that distinguishes between congested and uncongested conditions. In accordance with 23 CFR Part 490 (2024), state DOTs and Metropolitan Planning Organizations are required to assess traffic congestion for the purpose of carrying out the Congestion Mitigation and Air Quality program. For calculating the national performance management measures for traffic congestion, the congestion threshold speed is defined as “the speed of travel at which any slower measured speeds would result in excessive delay for travel time reporting segment”; and the speed threshold of 20 mph or 60% of PSL on a segment, whichever is greater, is used to calculate the Peak Hour Excessive Delay metric (23 CFR Part 490, 2024). The selection of congestion threshold speed can significantly impact the delay measure. The thresholds used by transportation agencies are typically classified into three main categories:

1. A designated speed for all study segments:
  - a. 35 mph (severe congestion) or 60 mph (congestion) (California DOT, 2023).
  - b. 45 mph (Minnesota DOT, 2022).
2. A percentage of reference speed (free-flow speed) or an offset from the free-flow speed:
  - a. 80% of reference speed (Schrank et al., 2024; Texas A&M Transportation Institute, 2023).
  - b. 90% of free-flow speed (FHWA, 2020).
  - c. Free-flow speed—20 mph (VDOT, 2023).
3. PSL or a percentage of PSL:
  - a. 70% of PSL (low) or 85% of PSL (high) (Washington DOT, 2018).
  - b. 60% of PSL (23 CFR Part 490, 2024).

### **Impacts of Reference Speed and Congestion Threshold on Performance Measures**

Traffic delay reduction and travel time reliability are frequently used as key performance indicators for evaluating project benefits (Peer et al., 2012; Williges and Mahdavi, 2008; Wolniak and Mahapatra, 2014; Xu and Lambert, 2015). Inconsistencies in delay threshold and reference speed across different projects can introduce bias in the comparison of performance outcomes. With data from nine freeway sections in Atlanta for 2010, Margiotta et al. (2015) studied the effect of using different reference speed estimates on delay calculation. The congestion thresholds tested were free-flow speed, maximum throughput speed (52 mph), 40 mph, and median speed for each segment. The results showed that the different congestion

thresholds produced quite different delay values, but the ranking of delay among the segments was the same for free-flow speed, maximum throughput speed, and 40 mph. The ranking produced by median speed was slightly different. This study recommended that analysts clearly document the congestion threshold and/or reference speed used to help interpret and understand the calculated performance measures. Poor selection of reference speed also has a high probability of leading to poor outcomes. For example, if the reference speed used is lower than the field-observed free-flow speed, the delay measure would be underestimated. Reference speed is particularly important for cost-benefit evaluation and improvement project prioritization for transportation agencies (Peer et al., 2012; Williges and Mahdavi, 2008; Wolniak and Mahapatra, 2014; Xu and Lambert, 2015). Appropriate reference speed selection and accurate performance measures enable transportation agencies to make informed decisions regarding infrastructure improvements and traffic management strategies. However, the impacts of the selection of reference speed and congestion threshold speed on performance measures are still not well studied in the literature.

This study conducts a comprehensive analysis of how the selection of reference speed impacts delay and reliability measures. Several reference speed estimation methods are compared for both interstate highways and arterials to gain insights into selecting appropriate reference speed.

## **Data Collection and Preparation**

### **Data Availability on Arterials**

This section compares the data availability provided by both NPMRDS and the INRIX datasets aggregated into 15-minute intervals on non-interstate National Highway System routes maintained by VDOT. Data availability is assessed through a sensitivity analysis by adjusting the confidence score threshold for INRIX and the data density threshold for NPMRDS. As Table 1 shows, the INRIX dataset demonstrates that 89% of arterial TMCs have at least 95% real-time data availability during the a.m. peak hours (6 a.m. to 10 a.m.). However, the availability drops during nighttime hours (10 p.m. to 6 a.m.), with approximately 81% of arterial TMCs meeting a minimum 50% data availability threshold, based on a confidence score of 28 or higher (Table 2).

**Table 1. Arterial TMC Segments Data Availability—INRIX a.m. Hours**

INRIX a.m.		Time Availability									
		100%	95%	90%	85%	80%	75%	70%	65%	60%	55%
Confidence Score	30	36	4609	4853	4966	5022	5048	5073	5097	5113	5123
		0.7%	89.0%	93.7%	95.9%	97.0%	97.5%	98.0%	98.4%	98.7%	98.9%
	29-30	41	4629	4875	4976	5024	5055	5079	5102	5117	5124
		0.8%	89.4%	94.1%	96.1%	97.0%	97.6%	98.1%	98.5%	98.8%	98.9%
	28-30	49	4680	4901	4997	5033	5065	5086	5108	5120	5124
		0.9%	90.4%	94.6%	96.5%	97.2%	97.8%	98.2%	98.6%	98.9%	98.9%
	27-30	54	4705	4913	5006	5039	5068	5089	5110	5120	5124
		1.0%	90.8%	94.9%	96.7%	97.3%	97.9%	98.3%	98.7%	98.9%	98.9%
	26-30	56	4736	4934	5019	5047	5079	5099	5116	5123	5126
		1.1%	91.4%	95.3%	96.9%	97.5%	98.1%	98.5%	98.8%	98.9%	99.0%
	25-30	56	4755	4950	5022	5048	5082	5101	5118	5123	5126
		1.1%	91.8%	95.6%	97.0%	97.5%	98.1%	98.5%	98.8%	98.9%	99.0%
	INRIX a.m.		Time Availability								
			50%	45%	40%	35%	30%	25%	20%	15%	10%
Confidence Score	30	5125	5131	5133	5136	5140	5148	5151	5157	5161	5167
		99.0%	99.1%	99.1%	99.2%	99.2%	99.4%	99.5%	99.6%	99.7%	99.8%
	29-30	5125	5132	5134	5136	5142	5148	5151	5158	5162	5168
		99.0%	99.1%	99.1%	99.2%	99.3%	99.4%	99.5%	99.6%	99.7%	99.8%
	28-30	5126	5132	5135	5136	5145	5149	5152	5158	5163	5168
		99.0%	99.1%	99.2%	99.2%	99.3%	99.4%	99.5%	99.6%	99.7%	99.8%
	27-30	5127	5132	5135	5136	5145	5149	5152	5158	5163	5169
		99.0%	99.1%	99.2%	99.2%	99.3%	99.4%	99.5%	99.6%	99.7%	99.8%
	26-30	5130	5132	5136	5138	5146	5150	5153	5158	5164	5169
		99.1%	99.1%	99.2%	99.2%	99.4%	99.4%	99.5%	99.6%	99.7%	99.8%
	25-30	5130	5134	5136	5140	5147	5150	5155	5158	5164	5169
		99.1%	99.1%	99.2%	99.2%	99.4%	99.4%	99.5%	99.6%	99.7%	99.8%

TMC = Traffic Message Channel.

**Table 2. Arterial TMC Segments Data Availability—INRIX Nighttime Hours**

INRIX Night		Time Availability										
		100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	
Confidence Score	30	0	558	1143	1721	2253	2699	3045	3386	3680	3921	
		0.0%	10.8%	22.1%	33.2%	43.5%	52.1%	58.8%	65.4%	71.0%	75.7%	
	29-30	0	579	1173	1753	2294	2739	3079	3417	3707	3952	
		0.0%	11.2%	22.6%	33.8%	44.3%	52.9%	59.4%	66.0%	71.5%	76.3%	
	28-30	0	634	1278	1852	2413	2838	3176	3498	3785	4010	
		0	558	1143	1721	2253	2699	3045	3386	3680	3921	
	27-30	0	664	1335	1942	2482	2899	3240	3550	3839	4036	
		0.0%	12.8%	25.8%	37.5%	47.9%	56.0%	62.5%	68.5%	74.1%	77.9%	
	26-30	0	724	1420	2058	2573	2978	3315	3628	3894	4103	
		0.0%	14.0%	27.4%	39.7%	49.7%	57.5%	64.0%	70.0%	75.2%	79.2%	
	25-30	0	736	1448	2079	2616	3006	3339	3647	3914	4118	
		0.0%	14.2%	27.9%	40.1%	50.5%	58.0%	64.4%	70.4%	75.5%	79.5%	
	INRIX Night		Time Availability									
			50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
Confidence Score	30	4107	4318	4510	4696	4821	4935	5001	5065	5105	5133	
		79.3%	83.3%	87.0%	90.6%	93.1%	95.3%	96.5%	97.8%	98.5%	99.1%	
	29-30	4134	4336	4538	4713	4839	4941	5002	5069	5108	5134	
		79.8%	83.7%	87.6%	91.0%	93.4%	95.4%	96.5%	97.8%	98.6%	99.1%	
	28-30	4214	4400	4603	4603	4868	4953	5014	5077	5110	5135	
		81.3%	84.9%	88.8%	88.8%	94.0%	95.6%	96.8%	98.0%	98.6%	99.1%	
	27-30	4246	4435	4634	4774	4881	4962	5022	5080	5112	5136	
		82.0%	85.6%	89.4%	92.1%	94.2%	95.8%	96.9%	98.1%	98.7%	99.1%	
	26-30	4296	4492	4665	4804	4897	4973	5038	5085	5117	5137	
		82.9%	86.7%	90.0%	92.7%	94.5%	96.0%	97.2%	98.1%	98.8%	99.2%	
	25-30	4315	4510	4681	4813	4903	4977	5040	5087	5117	5137	
		83.3%	87.0%	90.3%	92.9%	94.6%	96.1%	97.3%	98.2%	98.8%	99.2%	

TMC = Traffic Message Channel.

The NPMRDS has considerably lower availability. During a.m. hours (Table 3), 59.7% of arterial TMCs in the NPMRDS meet an 80% data availability threshold. For nighttime hours (Table 4), only 11.1% of arterial TMCs meet a minimum threshold of 50% data availability.

**Table 3. Arterial TMC Segments Data Availability—NPMRDS a.m. Hours**

NPMRDS a.m.		Time Availability									
		100%	95%	90%	85%	80%	75%	70%	65%	60%	55%
Confidence Score	C	0	1	2	2	4	9	17	26	41	50
		0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.3%	0.5%	0.8%	1.0%
	B-C	0	2	6	20	44	66	95	130	186	243
		0.0%	0.0%	0.1%	0.4%	0.8%	1.3%	1.8%	2.5%	3.6%	4.7%
	A-B-C	7	1616	2268	2737	3091	3403	3657	3863	4015	4177
		0.1%	31.2%	43.8%	52.8%	59.7%	65.7%	70.6%	74.6%	77.5%	80.6%
NPMRDS a.m.		Time Availability									
		50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
Confidence Score	C	69	88	108	153	203	269	326	404	499	757
		1.3%	1.7%	2.1%	3.0%	3.9%	5.2%	6.3%	7.8%	9.6%	14.6%
	B-C	304	348	405	469	561	676	823	1001	1240	1681
		5.9%	6.7%	7.8%	9.1%	10.8%	13.0%	15.9%	19.3%	23.9%	32.4%
	A-B-C	4307	4403	4505	4601	4680	4761	4816	4871	4936	4974
		83.1%	85.0%	87.0%	88.8%	90.3%	91.9%	93.0%	94.0%	95.3%	96.0%

NPMRDS = National Performance Management Research Data Set; TMC = Traffic Message Channel.

**Table 4. Arterial TMC Segments Data Availability—NPMRDS Nighttime Hours**

NPMRDS Night		Time Availability									
		100%	95%	90%	85%	80%	75%	70%	65%	60%	55%
Confidence Score	C	0	0	0	0	0	0	0	0	0	0
		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	B-C	0	0	0	0	0	0	0	0	0	0
		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	A-B-C	0	1	3	20	41	73	130	204	299	414
		0.0%	0.0%	0.1%	0.4%	0.8%	1.4%	2.5%	3.9%	5.8%	8.0%
NPMRDS Night		Time Availability									
		50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
Confidence Score	C	0	0	0	0	0	0	0	0	0	0
		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	B-C	0	0	0	0	0	0	0	0	0	3
		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.06%
	A-B-C	574	758	970	1219	1505	1939	2484	3080	3732	4388
		11.1%	14.6%	18.7%	23.5%	29.0%	37.4%	47.9%	59.4%	72.0%	84.7%

NPMRDS = National Performance Management Research Data Set; TMC = Traffic Message Channel.

### Comparison of Reference Speeds for Interstates

NPMRDS data from 2019 to 2021 were used in this part of the analysis. Five methods for estimating reference speed, as listed below, were analyzed.

1. PSL.
2. NPMRDS reference speed: NPMRDS reference speed is readily available in NPMRDS. This reference speed was determined as the 95th percentile of average speeds recorded from 10 p.m. to 5 a.m. during a 6-month period spanning from April 1 to September 30; from 2023, it is the 85th percentile of the speeds between 10 p.m. and 5 a.m. from March 1 to May 31 of the most recent NPMRDS map year (RITIS, 2024). NPMRDS reference

speed is rounded to the nearest integer. For each NPMRDS TMC segment, this study used the NPMRDS reference speed for 2019 to 2020.

3. Federal Highway Administration (FHWA) reference speed: This is the reference speed used in the Urban Congestion Report (FHWA, 2020). It is the 85th percentile of average speeds during defined off-peak periods on weekdays (9 a.m.–4 p.m., 7 p.m.–10 p.m.) and weekends (6 a.m.–10 p.m.).
4. Texas A&M Transportation Institute (TTI) reference speed: This reference speed is defined in the 2023 edition of *Texas Top 100 Most Congested Road Segments* (Texas A&M Transportation Institute, 2023). It is estimated by the 85th percentile of average speed between 10 p.m. and 6 a.m. on weekdays. If at least one-half of the 15-minute time periods on weeknights are not populated with a speed, the weeknight speeds are supplemented by weekday mid-day speeds (11 a.m. to 4 p.m.), and the 85th percentile of the combination of the overnight and mid-day speeds is used.
5. Jha reference speed: The study by Jha (2017) recommended the 85th percentile of average speeds from 9 p.m. to 6 a.m. on weekdays as the reference speed for freeways.

The latter three methods are all based on the 85th percentile of average segment speed in the low-traffic-volume period, but the time windows differ. The 85th-percentile speed indicates that 85% of average segment speeds are at or below this speed. For each TMC segment, the 85th percentile of average speed in each year using each of the three methods was calculated using the following steps:

1. From all the 15-minute aggregated speed data, create a dataset that includes data for the low-volume time window defined by the method.
2. Organize the 15-minute speeds in the dataset in ascending order, from the lowest speed to the highest.
3. Use the equation below to determine the index for the 85th percentile.

$$P = \frac{N + 1}{100} \times k$$

Where:

$P$  = index position.

$N$  = total number of data points.

$k$  = desired percentile ( $k = 85$ ).

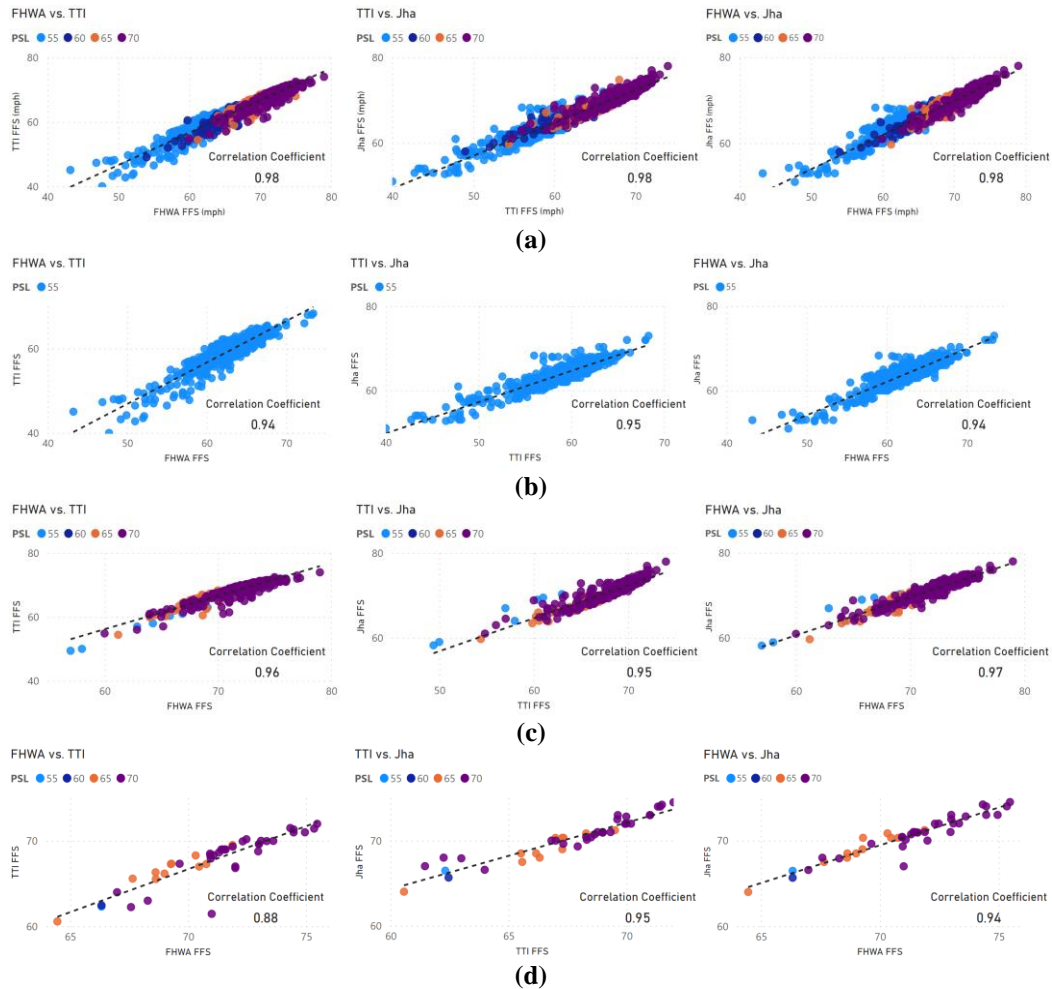
4. Determine the 85th-percentile speed using index position. If  $P$  is a whole number, the 85th-percentile speed is the speed at that index in the sorted dataset. If  $P$  is not a whole number, round it up to the nearest whole number to ascertain the corresponding speed.

A detailed step-by-step example of the reference speed calculation procedure is provided in Appendix A.

This study explored the correlations among the five sets of reference speeds through comparative analyses. The reference speeds derived from the “percentile-of-speed” category were compared against PSL.

## Comparison Among Three Methods

Comparisons of reference speeds from the FHWA, TTI, and Jha methods are presented in Figure 1. Only the results for 2019 are shown here. However, the findings remained consistent throughout the 3-year study period from 2019 to 2021.



**Figure 1. Comparison Among FHWA, TTI, and Jha Reference Speeds (a) Across All Roadway Segments; (b) on Segments with Posted Speed Limits of 55 mph; (c) Rural Segments; and (d) Segment Lengths Between 4 to 5 miles. FFS = free-flow speed; FHWA = Federal Highway Administration; PSL = posted speed limit; TTI = Texas A&M Transportation Institute.**

Figure 1a shows the pairwise comparisons among the three sets of reference speeds. The comparisons show a strong correlation between the methods, with a correlation coefficient of 0.98 for each pair. This finding was further supported by the analyses for different TMC segment groups. Figure 1b depicts the correlations among the three sets of reference speeds for segments with a PSL of 55 mph. The correlation coefficients were between 0.94 and 0.95. The strong correlations were also observed for other groups of different PSLs (55, 60, 65, and 70 mph), with correlation coefficients ranging from 0.91 to 0.97. The comparisons were also conducted for segments grouped by other attributes, such as urban/rural designation, the number of through lanes, and segment length. Figures 1c and 1d present an example of comparisons for rural segments and segments between 4 to 5 miles long, respectively. The results demonstrate high

correlations among the three methods across different segment groups. For urban segments, the pairwise correlation coefficient was 0.97 for each pair, and for rural segments, the coefficients were between 0.95 to 0.97. For segments with lengths from 0 to 9 miles, analyses were performed on each 1-mile bin. The results showed correlation coefficients between 0.76 to 0.99. The lower value of 0.76 may be attributed to the small number of long segments. Only 58 segments were longer than 6 miles. From all the comparisons for various groups, the reference speeds produced by all three methods exhibit high consistency, irrespective of different roadway attributes such as PSL, urban or rural setting, segment lengths, and the number of through lanes.

### Comparisons with Posted Speed Limit

Table 5 shows the differences between the three reference speeds derived from the 85th-percentile speed in low traffic conditions and the PSLs for urban and rural segments. Each row in the table provides results for a specific PSL and urban-rural combination, and the columns display the maximum (Max), average (Avg), and minimum (Min) differences as well as variance (Var) and sample size. The results for segments with PSLs of 50 and 60 mph in rural areas are unavailable because of the small sample size of two. Similarly, for segments with a PSL of 55 mph in rural areas, the results need to be interpreted with caution because there were only seven samples. For all other groups, the sample sizes were mostly greater than 100.

**Table 5. Comparisons Between Reference Speeds and Posted Speed Limit for Urban and Rural Segments**

PSL	Urban/ Rural	FRS-PSL (mph)				JRS-PSL (mph)				TRS-PSL (mph)				Sample Size
		Max	Avg	Var	Min	Max	Avg	Var	Min	Max	Avg	Var	Min	
55	Rural	-	-	-	-	-	-	-	-	-	-	-	-	7
55	Urban	18.4	7.5	14.5	-11.8	18.0	8.9	10.7	-4.0	13.3	4.2	16.1	-15.0	601
60	Rural	-	-	-	-	-	-	-	-	-	-	-	-	2
60	Urban	10.9	6.3	6.7	-6.0	10.5	6.6	4.7	-2.0	8.5	2.6	9.0	-11.0	215
65	Rural	8.8	4.7	5.6	-3.8	8.0	4.2	6.2	-5.3	5.9	1.6	8.4	-10.6	84
65	Urban	10.0	4.8	3.8	-0.9	9.8	4.9	2.7	-0.5	6.5	1.4	4.4	-7.7	166
70	Rural	9.0	2.3	5.8	-10.0	8.0	1.6	5.2	-9.0	4.0	-1.1	6.6	-15.2	473
70	Urban	6.0	1.8	3.2	-6.3	5.0	1.4	3.0	-7.0	1.7	-1.5	4.0	-11.0	250
<b>All</b>	<b>All</b>	<b>18.4</b>	<b>4.8</b>	<b>14.0</b>	<b>-11.8</b>	<b>18.0</b>	<b>5.1</b>	<b>17.1</b>	<b>-9</b>	<b>13.3</b>	<b>1.4</b>	<b>15.3</b>	<b>-15.2</b>	<b>1798</b>

Avg = average; FRS = Federal Highway Administration reference speed; JRS = Jha reference speed; Max = maximum; Min = minimum; MPH = miles per hour; PSL = posted speed limit; TRS = Texas A&M Transportation Institute reference speed.

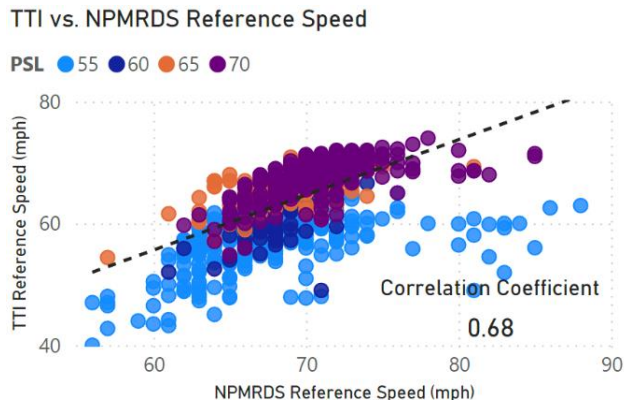
The comparison results suggest that the reference speeds derived from the 85th-percentile speed in low-volume conditions were generally greater than PSLs, and the differences between reference speed and PSL decrease as PSL increases. The differences for segments with lower PSLs demonstrated greater variances. In addition, the differences between reference speed and PSL estimates and PSL in rural segments displayed higher averages and variance than those observed in urban segments.

Among the three sets of reference speeds, the TTI reference speed had relatively smaller differences from PSL, regardless of PSL or urban/rural setting. The average differences between the reference speeds from the FHWA, Jha, and TTI methods and the PSL were 4.9 mph, 5.1 mph, and 1.4 mph, respectively.

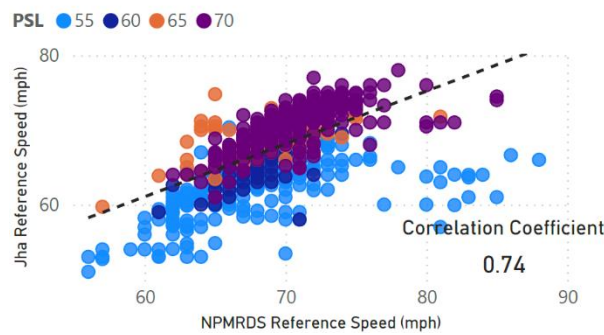
Another reference speed used by some agencies is the PSL plus 5 mph. PSL is available in the agency's roadway inventory data. This method is straightforward. In practice, the 85th-percentile speed is often used as a guide in setting or adjusting the PSL of a facility. From Table 5, reference speeds from FHWA and Jha methods typically exceed PSL by around 5 mph, which indicates this method was a good approximation of those two. However, the results were unstable and fluctuated with PSL: for segments with lower PSLs, the reference speeds were generally more than 5 mph above PSL, and for segments with higher PSLs, the differences tended to be smaller than 5 mph.

### **Comparison with NPMRDS Reference Speed**

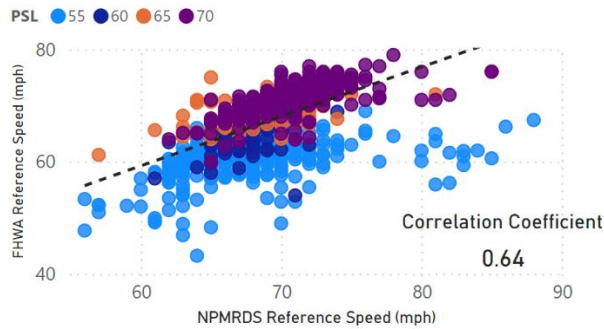
Many transportation agencies also use the NPMRDS reference speed. The comparisons between NPMRDS reference speed and the reference speeds from FHWA, TTI, and Jha methods are shown in Figure 2. The color of each point indicates the PSL on a segment. The correlations between NPMRDS reference speed and the other reference speeds were relatively low, with correlation coefficients between 0.64 to 0.74. These values are much lower than the correlation coefficient of 0.98 among the other three sets of reference speeds. NPMRDS reference speed values showed significantly larger variability than the other three sets of reference speeds. The trends for segments with the same PSL were not clear. For example, NPMRDS reference speed varied significantly from 56 to 88 mph for segments with a PSL of 55 mph and from 62 to 85 mph for segments with a PSL of 70 mph. Some extremely high values, such as 88 mph, were observed, likely because NPMRDS reference speed is based on 95th-percentile speed representing the highest 5% of observed speeds. Directly using NPMRDS reference speed as a benchmark to calculate delay may not be appropriate because of this variability.



**(a) Comparison Between TTI and NPMRDS Reference Speeds**  
 Jha vs. NPMRDS Reference Speed



**(b) Comparison Between Jha and NPMRDS Reference Speeds**  
 FHWA vs. NPMRDS Reference Speed



**(c) Comparison Between FHWA and NPMRDS Reference Speeds**

**Figure 2. Comparison of FHWA, TTI, and Jha Reference Speeds with NPMRDS Reference Speed. FHWA = Federal Highway Administration; NPMRDS = National Performance Management Research Data Set; PSL = posted speed limit; TTI = Texas A&M Transportation Institute.**

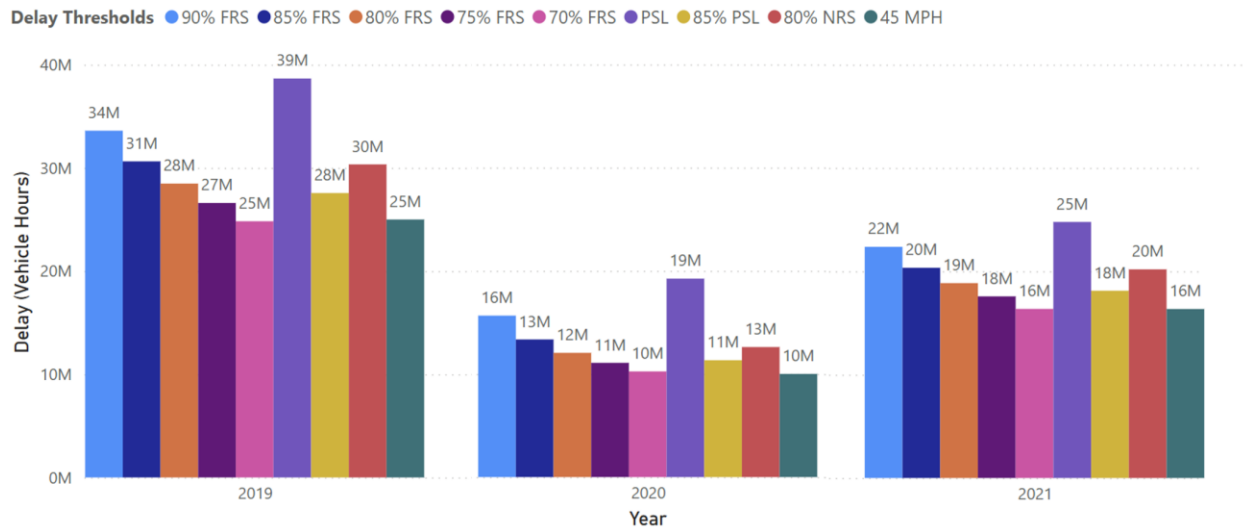
### Comparison of Congestion Threshold Speeds and Delay

Using NPMRDS data from 2019 to 2021 on all interstate highways in Virginia, the impact of differences between congestion threshold speeds on delay estimation was evaluated in terms of delay values and ranking among segments. The comparisons were conducted at the network, district, and corridor levels. In consultation with the Technical Review Panel of this study, the following congestion thresholds were selected for comparison:

- Percentage of FHWA reference speed: (a) 90%, (b) 85%, (c) 80%, (d) 75%, and (e) 70% of reference speed from the FHWA method.
- Percentage of PSL: (a) 100% and (b) 85% of PSL.
- Percentage of NPMRDS reference speed: 80% of NPMRDS reference speed.
- Fixed threshold: a constant of 45 mph.

## Statewide Analysis

A comparison of statewide delay in units of vehicle-hours was calculated using nine different congestion thresholds (Figure 3). As expected, higher thresholds, such as the 90% of FHWA reference speed, led to greater delay compared with lower thresholds, like the 70% of FHWA reference speed. The increase in delay value was more noticeable when moving from high to highest threshold (e.g., from 85 to 90% of FHWA reference speed) than when moving from low to moderate threshold (e.g., from 70 to 75% FHWA reference speed), which is probably because high thresholds can capture minor speed reductions, whereas lower thresholds capture only severe congestion. Because severe congestion is less common than minor and moderate congestion, the overall change in delay value is less pronounced when changing between lower thresholds. However, depending on the magnitude of the delay, the percentage change in delay might not follow the same trends.



**Figure 3. Comparison of Statewide Vehicle-Hours of Delay Based on Different Congestion Thresholds. MPH = miles per hour; NRS = National Performance Management Research Data Set reference speed; PSL = posted speed limit; FRS = Federal Highway Administration reference speed.**

Using PSL as a congestion threshold resulted in the highest delay value, and using the threshold of 45 mph produced the lowest delay estimate. For all the delay estimates, a notable decrease occurred in 2020, which was caused by the lower traffic volume during the COVID-19 pandemic. Increases occurred in 2021, but all the estimated delays remained below the pre-pandemic levels. The delay calculated relative to the PSL was approximately 1.56 times of that relative to the threshold of 45 mph, but this ratio rose to 1.9 in 2020. The increase may be attributed to the reduced traffic during the pandemic, which decreased the occurrence of severe congestion that can be captured by the 45-mph threshold.

Considerable variations occurred among the statewide delays estimated based on different congestion thresholds, which highlights the significant impact of the selection of congestion threshold on estimated delay values and the need for a consistent delay method to prevent potential bias in performance measurement activities.

### Districtwide Analysis

A comparison of delays across eight of the nine districts of VDOT was conducted (Figure 4). No interstate highways are in the Lynchburg district, so it was not included. The results for 2019 are shown in Table 6. Results for 2020 and 2021 reveal similar trends. The thresholds of 85 and 90% of FHWA reference speed produced the same rankings, as did the 70, 75, and 80% of FHWA reference speed, and the 85% of PSL, 80% of NPMRDS reference speed, and 45 mph. For the delays estimated based on all nine congestion thresholds, the Northern Virginia district, ranked sixth in total interstate mileage and with the most populated urban areas in the state, experienced the highest delay, followed by the Hampton Roads district, which has the third largest interstate mileage and dense urban areas. It applies to results from all the congestion thresholds. Similarly, the districts with the least total delay, Bristol and Culpeper, remain the same ranks for all nine congestion thresholds. For the rest of the four districts, their ranks fluctuate within one position for different congestion thresholds. Although the Richmond district has the largest interstate mileage, it ranked third in total delay. It shows that total districtwide delay may not directly correlate with the amount of mileage in each district.

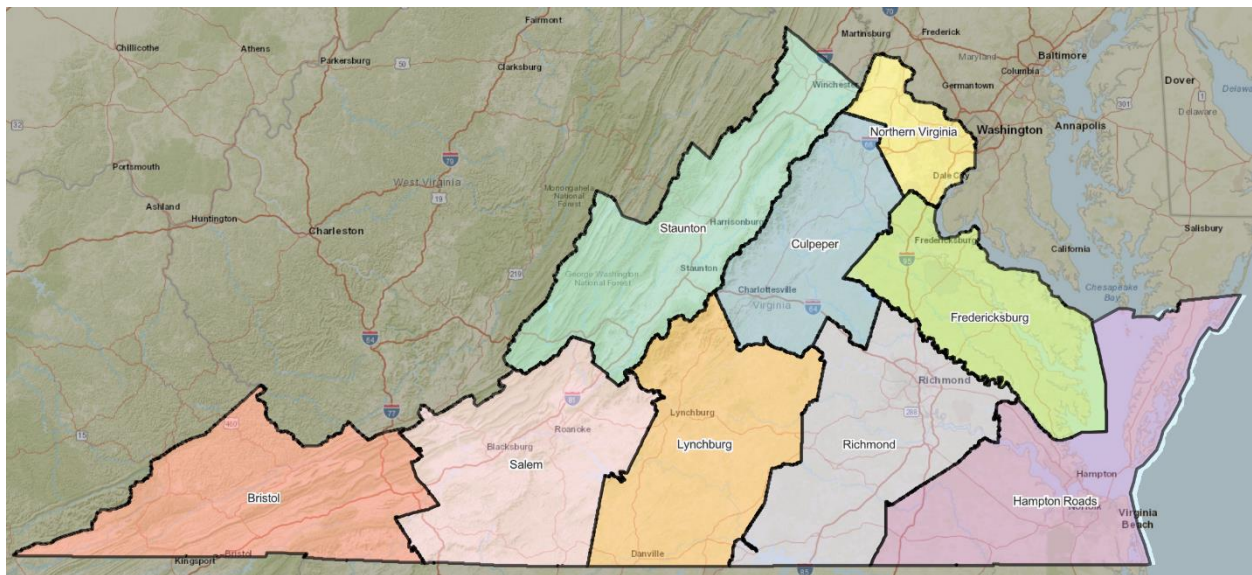


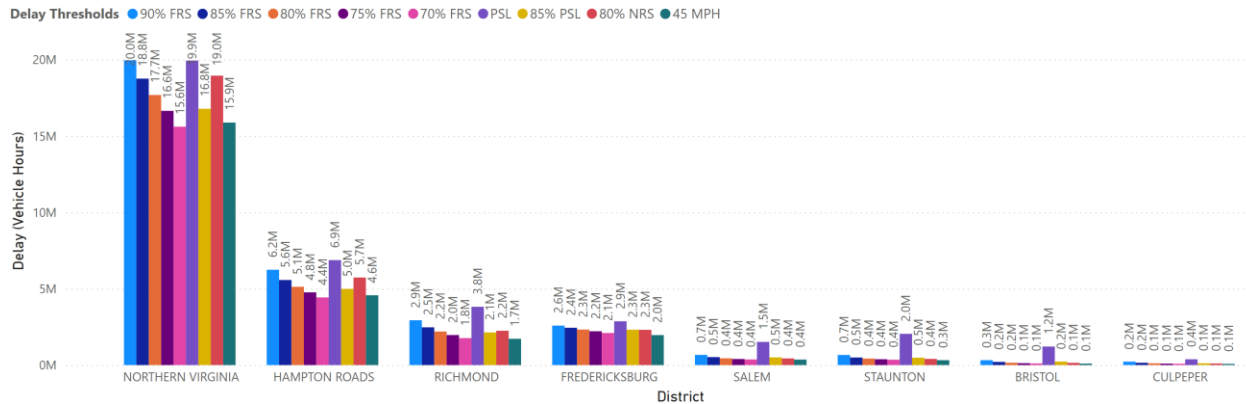
Figure 4. Nine Districts of Virginia Department of Transportation

**Table 6. Total Mileage and Delay Ranking by District**

District	Total Mileage (mile)	Rank of Total Delay by Threshold			
		90% and 85% FRS	80%, 75%, or 70% FRS	PSL	85% PSL, 80% NRS, or 45 mph
Richmond	514.6	3	4	3	4
Staunton	462.4	6	6	5	6
Hampton Roads	311.2	2	2	2	2
Bristol	241.3	7	7	7	7
Salem	239.0	5	5	6	5
Northern Virginia	222.8	1	1	1	1
Fredericksburg	99.0	4	3	4	3
Culpeper	98.8	8	8	8	8

FRS = Federal Highway Administration reference speed; mph = miles per hour. NRS = National Performance Management Research Data Set reference speed; PSL = posted speed limit.

From Figure 5, using either the 90% of FHWA reference speed or PSL as the congestion threshold resulted in the highest delay for each district. In the Northern Virginia and Fredericksburg districts, delays calculated relative to the 90% of FHWA reference speed were higher than those calculated relative to PSL, but in the other districts, using PSL produced higher delays.



**Figure 5. Comparison of Districtwide Vehicle-Hours of Delay Based on Different Congestion Thresholds. MPH = miles per hour; NRS = National Performance Management Research Data Set reference speed; PSL = posted speed limit; FRS = Federal Highway Administration reference speed.**

Table 7 illustrates that the difference between the FHWA reference speed and PSL varied across districts, as well as the differences between 90% of FHWA reference speed and PSL. In general, when PSL is greater than the 90% of FHWA reference speed, the delay calculated relative to PSL tends to be higher than the delay relative to 90% of FHWA reference speed.

**Table 7. Posted Speed Limit and FHWA Reference Speed by District**

District	Average of PSL	Average of FRS	Average of (FRS-PSL)	Average of (90% FRS-PSL)
Northern Virginia	56.3	64.1	7.8	1.4
Hampton Roads	59.4	66.0	6.6	- 0.0
Richmond	63.2	69.4	6.2	- 0.8
Fredericksburg	66.6	71.6	5.0	- 2.2
Culpeper	67.8	72.8	5.0	- 2.3
Salem	64.5	67.6	3.1	- 3.7
Staunton	68.8	71.6	2.7	- 4.4
Bristol	69.1	70.4	1.2	- 5.8

FHWA = Federal Highway Administration; FRS = FHWA reference speed; PSL = posted speed limit.

### Corridor Level Analysis

A corridor level analysis was conducted using two major commuter corridors, I-66 eastbound (I-66E) and I-395 northbound (I-395N), in the VDOT Northern Virginia district. The two corridors, shown in Figure 6, carry significant traffic to Washington, D.C. The Average Annual Daily Traffic (AADT) on the segments of this corridor ranged from 35,858 to 107,990 vehicles in 2019. On average, the segments on I-395N carried larger volumes than those on I-66E. Table 8 shows the delay calculated using six congestion thresholds for the morning peak hours from 6 a.m. to 8 p.m. in 2019. For I-395N, using 80% of NPMRDS reference speed as the congestion threshold produced the highest total delay, whereas for I-66E, both the 90% FHWA reference speed and PSL thresholds resulted in the highest total delay, followed by 80% of reference speed. The estimated total delay on I-66E was higher than that on I-395N when using PSL, 80% and 90% of FHWA reference speed, and 80% of NPMRDS reference speed as the congestion threshold. However, when using lower thresholds of 70% of FHWA reference speed and 45 mph, the estimated total delay on I-395N was greater, which may indicate that I-395N encountered more severe congestion with large speed drops. I-66E is approximately twice the length of I-395N. Normalizing delay values by corridor length, I-395N experienced a much higher average delay per mile compared with I-66E, regardless of the threshold speeds used for calculations. The corridor-level comparisons further confirmed that different congestion thresholds could produce very different delay values, highlighting the importance of having a consistent method for performance measurement. The normalized delay values across different thresholds consistently show that I-395N experiences more delay per mile than I-66E, highlighting that normalized delay better reflects the relative severity of congestion on these two corridors compared with total delay. This finding emphasizes the importance of selecting an appropriate delay metric for the purpose of delay ranking and project prioritization.



**Figure 6. Commuting Corridors of Interstate 66 Eastbound and Interstate 395 Northbound. AADT = Average Annual Daily Traffic.**

**Table 8. Estimated Corridor Delays in 2019**

	Delay (vehicle-hours) Under Different Congestion Thresholds						
	Threshold	PSL	90% FRS	80% FRS	70% FRS	80% NRS	45 mph
<b>I-395N</b>	Total	1,844,682	1,837,350	1,651,944	1,484,327	1,881,445	1,559,865
	Delay per Mile	183,310	182,333	163,665	146,919	186,913	154,527
<b>I-66E</b>	Total	1,925,097	1,927,980	1,665,607	1,422,298	1,909,922	1,515,820
	Delay per Mile	100,536	100,606	87,176	74,773	99,944	79,724

FRS = Federal Highway Administration reference speed; mph = miles per hour. NRS = National Performance Management Research Data Set reference speed; PSL = posted speed limit.

### Comparison of Travel Time Reliability

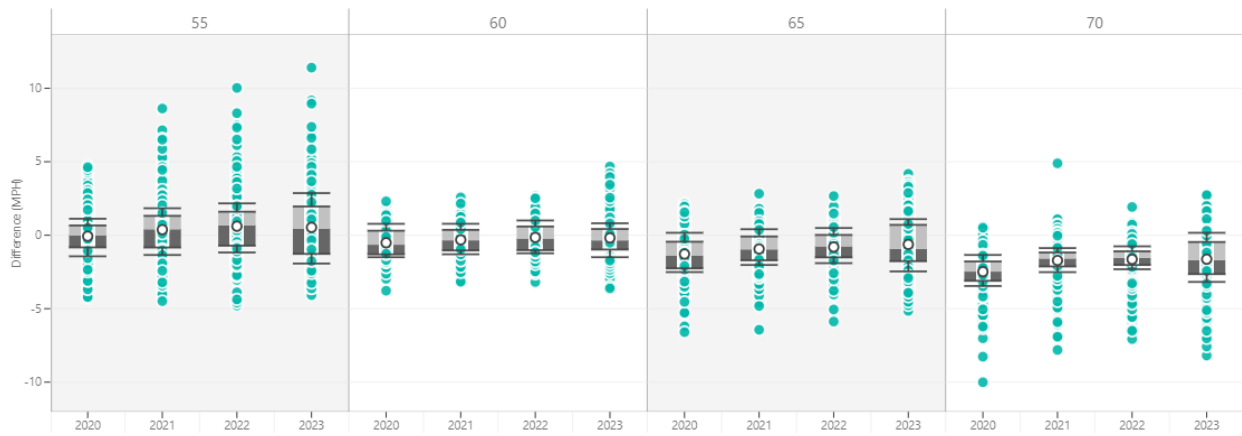
According to the Technical Review Panel, VDOT uses INRIX data in most of the delays and analyses, and NPMRDS is mainly used for meeting the performance reporting and target-setting requirements mandated by the FHWA. Based on their suggestions, analyses were conducted using INRIX data to investigate what effect different reference speed methods have on calculated PTI. Using probe speed data from INRIX for all interstate highways in Virginia, this study calculated reference speed and PTI using different methods and compared the results in terms of PTI value and relative ranking among roadway segments. The study period was from 2020 to 2023, and 15-minute speeds of all confidence scores (30, 20, or 10) were used in the analyses. Due to data quality issues, the TMC segments shorter than 0.1 mile were excluded from the analysis. The length and location of TMC segments could change as the data provider updates their coverage maps. Only those TMC segments that remained unchanged during the study years were used in the analysis to provide a fair comparison across different years. A total of 1,875 interstate TMC segments were studied. The FHWA and TTI reference speeds were calculated with INRIX data and compared with the INRIX reference provided by the data vendor.

## Difference Between Reference Speeds

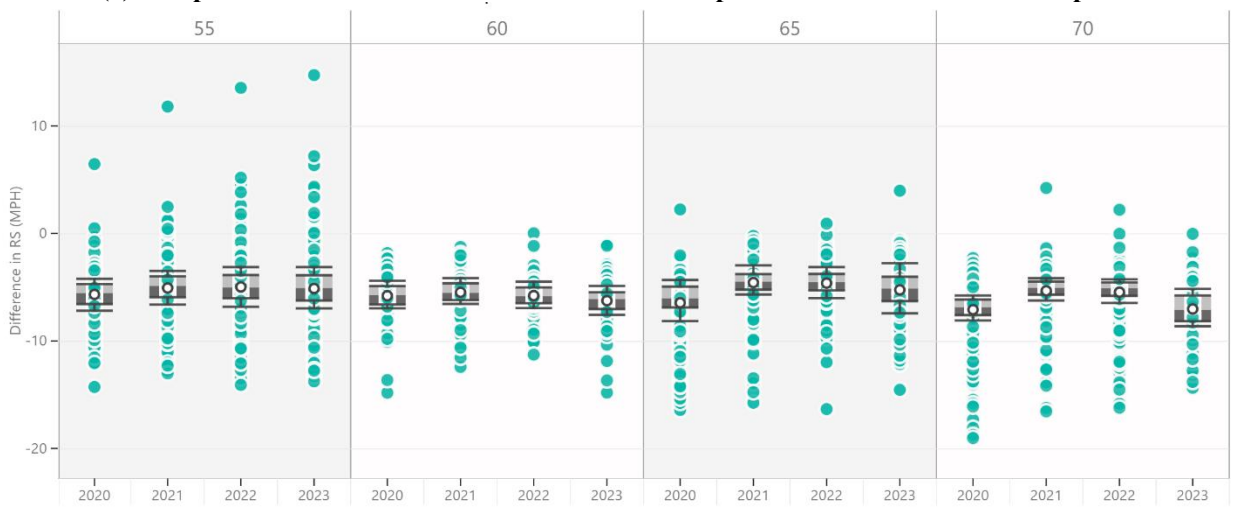
The differences and similarities between FHWA, TTI, and NPMRDS reference speeds have been compared using NPMRDS data in the previous sections. Here, the FHWA and TTI reference speeds were calculated with INRIX data to allow for a fair comparison with INRIX reference speed and to better understand the impact of their differences on PTI calculated relative to them. The FHWA and TTI reference speeds were the 85th percentile of average segment speed in low traffic volume time periods defined by different time windows, whereas the INRIX reference speed represents the 66th-percentile speed on a segment for all time periods (RITIS, 2024).

### *Differences of Reference Speeds Across Methods*

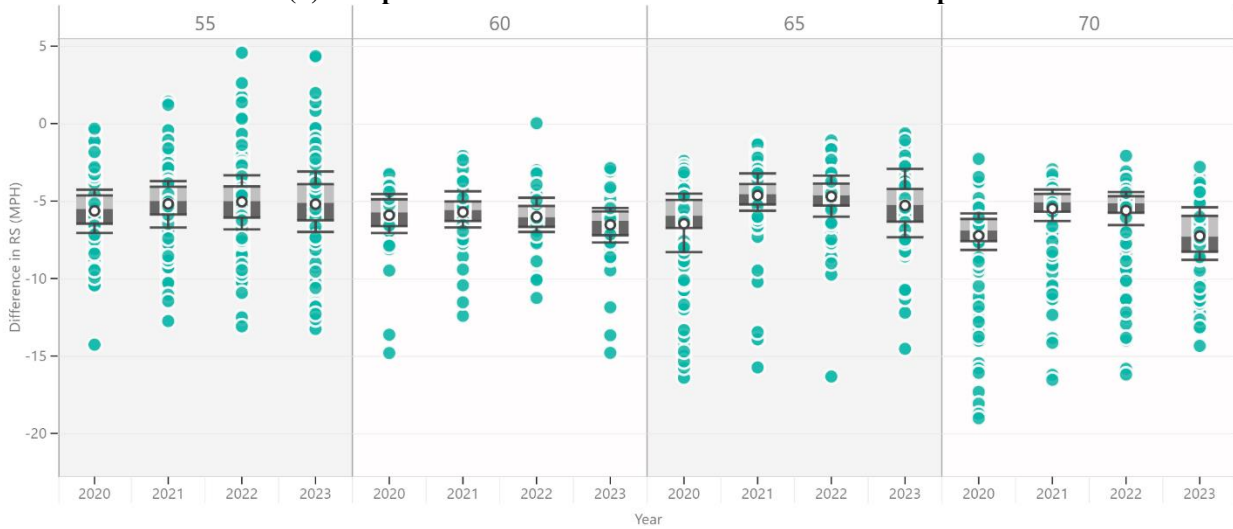
The differences between the three sets of reference speeds across various years by PSL are visualized in Figure 7. Each sample represents the difference between two reference speeds calculated with different methods for a single TMC segment. The whiskers in the box-and-whisker plots in Figure 7 represent the 15th and 85th percentiles of the differences between the two sets of reference speeds. In Figure 7a, positive values indicate that the TTI reference speed is higher than the FHWA one. For segments with PSLs ranging from 55 to 70 mph, the differences between the 15th to 85th percentiles were all within plus or minus 5 mph, indicating that, for most of the segments, the reference speeds from the three methods are similar. From 2020 to 2023, the overall patterns remain consistent, with a slight increase in variability. Only a few TMC segments had PSLs of 35 mph (three samples) and 45 mph (eight samples), which were either interchange segments or urban interstate segments that connect to local arterials. Therefore, they were not shown in Figure 7. These segments were not included in Figure 7 because of the small sample size. As the PSLs increase, the reference speeds estimated from the FHWA method are generally higher than those from the TTI method. Because the larger differences and higher PSLs were usually observed on segments with higher truck traffic volumes, one potential explanation for this trend is that the TTI method uses mainly nighttime speeds that tend to be lower due to a higher percentage of truck traffic, and mid-day data are only added when at least one-half of the 15-minute time periods on weeknights are not populated with a speed. The FHWA method uses more mid-day speeds, which comprise more passenger car traffic that is likely to travel faster than trucks.



(a) Comparison Between FHWA and TTI Reference Speeds Calculated with INRIX Speed Data



(b) Comparison Between FHWA and INRIX Reference Speeds



(c) Comparison Between FHWA and INRIX Reference Speeds on External Segments

**Figure 7. Box-and-Whisker Plot of Differences Among FHWA, TTI, and INRIX Reference Speed by Posted Speed Limit and Year. FHWA = Federal Highway Administration; MPH = miles per hour; TTI = Texas A&M Transportation Institute.**

From Figure 7b, the differences between FHWA and INRIX reference speeds are significantly greater than those between FHWA and TTI reference speeds, both in magnitude and variance. This trend is observed across segments of different PSLs. A positive value in this figure indicates that the INRIX reference speed is higher than the FHWA one. The average difference was -4.43, -3.42, -3.26, and -3.78 for the years 2020 to 2023, respectively. In general, the INRIX reference speed was lower than the FHWA value. This discrepancy can be attributed to INRIX adopting a lower percentile, specifically the 66th percentile, across all time periods, whereas the FHWA method employs the 85th percentile during low traffic periods when speeds are comparatively higher.

A few outliers were in Figure 7b for the segments with PSL of 55. All four segments were on interchanges; they were considered as “internal” segments in the NPMRDS. Two types of TMC segments are in NPMRDS: internal and external segments. The internal segment refers to the area slightly past the decision point (e.g., merging and diverging areas on freeways) or intersection, and the external segment refers to the section of the road leading up to the decision point (e.g., segments between interchanges on freeways; Schuman et al., n.d.). The speeds on the two types of segments were computed separately because the speed profiles may be substantially different because of different traffic characteristics (Schuman et al., n.d.). More vehicle interactions are on interval segments, which could potentially cause large variations in the speeds of individual vehicles. Compared with the 85th-percentile speed, the 66th percentile is relatively stable. Figure 7c shows the difference between FHWA and TTI reference speeds for external segments only. The variations in internal segments were considerably smaller compared with those for all segments in Figure 7b.

The average differences between the reference speeds from FHWA and TTI methods are generally less than 3 mph, as shown in Table 9. The number of segments with an absolute difference of more than 5 mph ranges from 18 to 35 out of the total of 1,959 segments each year. Spanning from 2020 to 2023, a difference of less than 5 mph was observed on 97.5% of the TMC segments. The maximum absolute difference in reference speeds throughout the study period is 11.37 mph, which was observed on an interchange segment in 2023.

**Table 9. Average Differences Between FHWA and TTI Reference Speeds**

<b>Year</b>	<b>Posted Speed Limit (mph)</b>	<b>Average Differences (mph)</b>	<b># of Segments with Absolute Difference &gt; 5 mph</b>
2020	35	0.78	23
	45	0.1	
	55	- 0.1	
	60	- 0.55	
	65	- 1.32	
	70	- 2.51	
2021	35	2.38	18
	45	0.76	
	55	0.34	
	60	- 0.35	
	65	- 0.97	
	70	- 1.75	
2022	35	1.89	18
	45	1.17	
	55	0.58	
	60	- 0.18	
	65	- 0.84	
	70	- 1.67	
2023	35	1.18	35
	45	0.89	
	55	0.5	
	60	- 0.22	
	65	- 0.66	
	70	- 1.66	

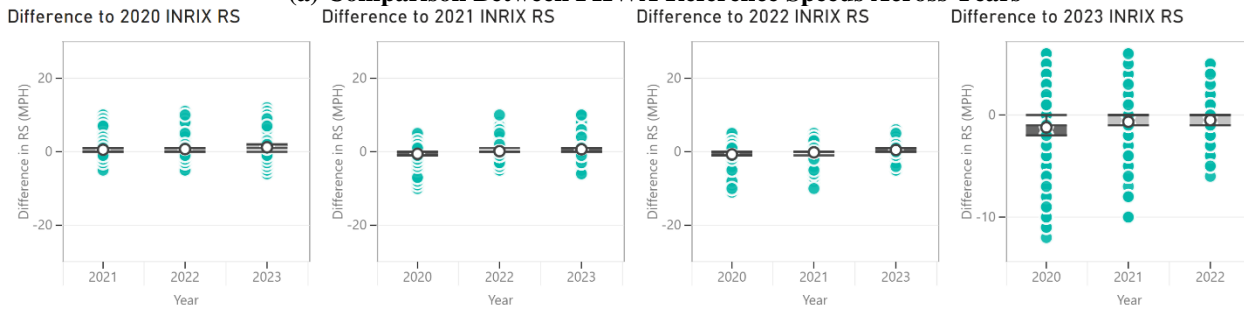
FHWA = Federal Highway Administration; mph = miles per hour; TTI = Texas A&M Transportation Institute.

### *Differences of Reference Speeds Across Years*

Figure 8 shows the differences among reference speeds of each study year for the FHWA and INRIX reference speeds. Each plot compares the reference speeds of a specific year with those of the rest of the study years. The average differences across 2020 to 2023 for the FHWA reference speed are shown in Table 10.



(a) Comparison Between FHWA Reference Speeds Across Years



(b) Comparison Between INRIX Reference Speeds Across Years

**Figure 8. Box-and-Whisker Plot of Year-to-Year Differences for FHWA Method. FHWA = Federal Highway Administration; RS = reference speed.**

From Figure 8 and Table 10, the average differences of FHWA reference speeds across the study years were relatively small, similar to the trends observed in the differences between FHWA and TTI reference speeds. However, the variances of the between-year differences were much larger than the variances of the differences between the two methods shown in Figure 7a. For the TTI reference speeds, the yearly trends across years closely mirrored those in the FHWA reference speeds, so they are not shown here. INRIX reference speeds also changed throughout the study years, but differences were relatively smaller than those observed in FHWA and TTI reference speeds, with the median difference close to zero and a narrower width between the 15th and 85th percentiles of the between-year differences. The average differences between 2023 INRIX reference speed and those for the years 2020, 2021, and 2022 were 1.22, 0.66, and 0.5, respectively, which are within a similar range to the FHWA reference speeds across the same years.

**Table 10. Average Differences of FHWA Reference Speeds Across Years 2020 to 2023**

Year	Avg. Difference to 2020 Reference Speed (mph)	Avg. Difference to 2021 Reference Speed (mph)	Avg. Difference to 2022 Reference Speed (mph)	Avg. Difference to 2023 Reference Speed (mph)
2020	-	-0.7	-0.5	0.82
2021	0.7	-	0.21	1.53
2022	0.5	-0.21	-	1.32
2023	-0.82	-1.53	-1.32	-
<b>Average</b>	<b>0.67</b>	<b>-0.81</b>	<b>-0.54</b>	<b>0.122</b>

Avg. = average; FHWA = Federal Highway Administration; mph = miles per hour.

The results of the year-to-year comparison indicate that the FHWA and TTI methods produce very similar reference speeds that are generally higher than INRIX reference speeds. The reference speeds can change over time. The changes are anticipated because of the changes in factors influencing reference speed, such as roadway geometry and capacity. This observation

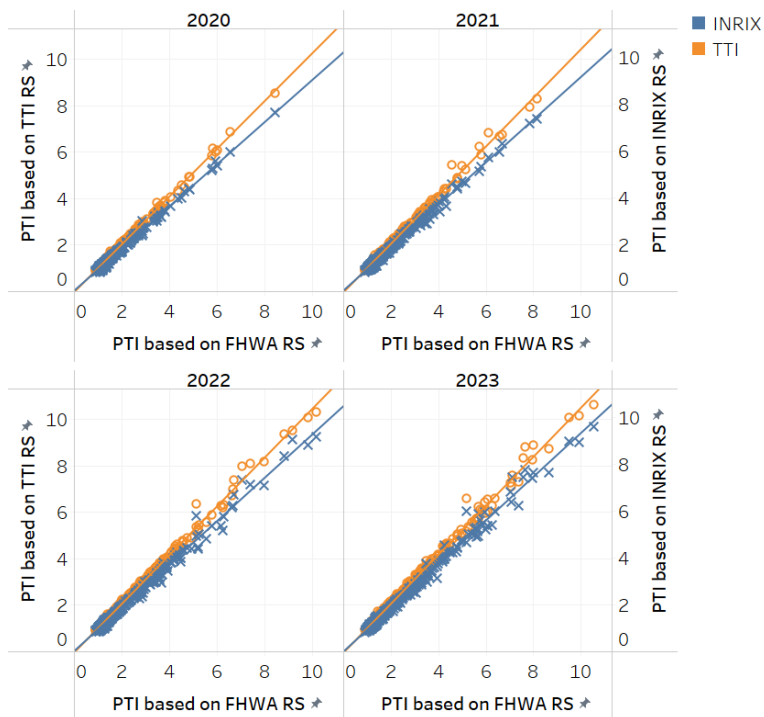
also highlights the need to update reference speed to capture the benefit of traffic improvement projects.

### **Comparison of PTIs Calculated with Different Free-Flow Speed Estimates**

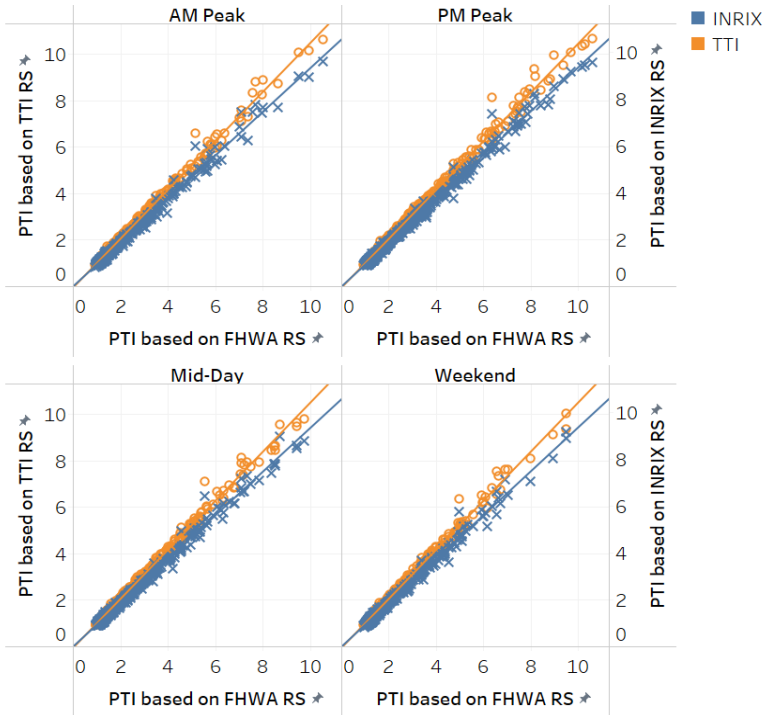
PTIs calculated based on FHWA, TTI, and INRIX reference speeds were analyzed to evaluate how the variations in reference speeds influence the application of travel time reliability measures.

#### *Differences in PTI Values*

Figure 9a presents a scatter plot comparing the PTI values calculated based on the three sets of reference speeds for the morning peak period from 2020 to 2023. The PTI values calculated using FHWA, TTI, and INRIX reference speeds show a high degree of correlation, with correlation coefficients for each two sets of PTI higher than 0.99 in all 4 years. On average, the TTI reference speed produced the highest PTI values, followed by the FHWA reference speed. The INRIX reference speed resulted in slightly lower PTI values. As discussed in the previous section, INRIX reference speed was lower than the other two, leading to longer travel time under reference speed and, thus, lower PTI values. However, the differences were small. These high correlations suggest that the minor discrepancies in reference speed may have minimal impact on PTI values and, thus, have no significant impact on travel time reliability evaluation using PTI.



(a) Comparison of PTI in a.m. Peak Period by Reference Speed Used and Year



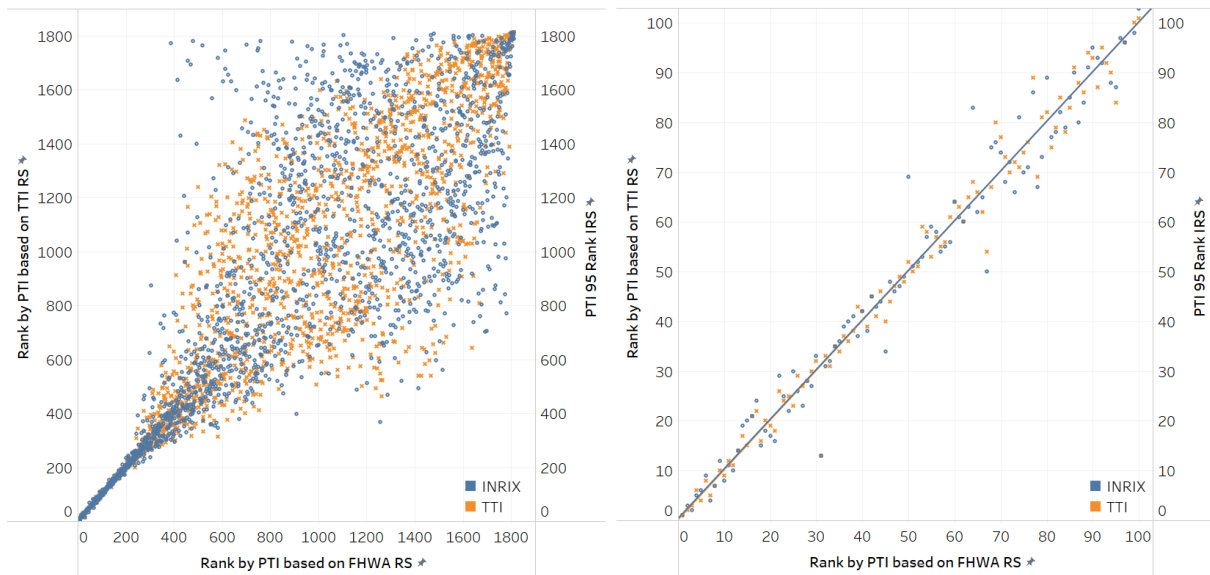
(b) Comparison of PTI by Reference Speed Used and Time of Day in 2023

Figure 9. PTI Calculated Based on FHWA, TTI, and INRIX Reference Speeds for (a) a.m. Peak Period in Different Years and (b) Different Time Periods in 2023. FHWA = Federal Highway Administration; PTI = Planning Time Index; RS = reference speed; TTI = Texas A&M Transportation Institute.

### *Differences in PTI Ranks*

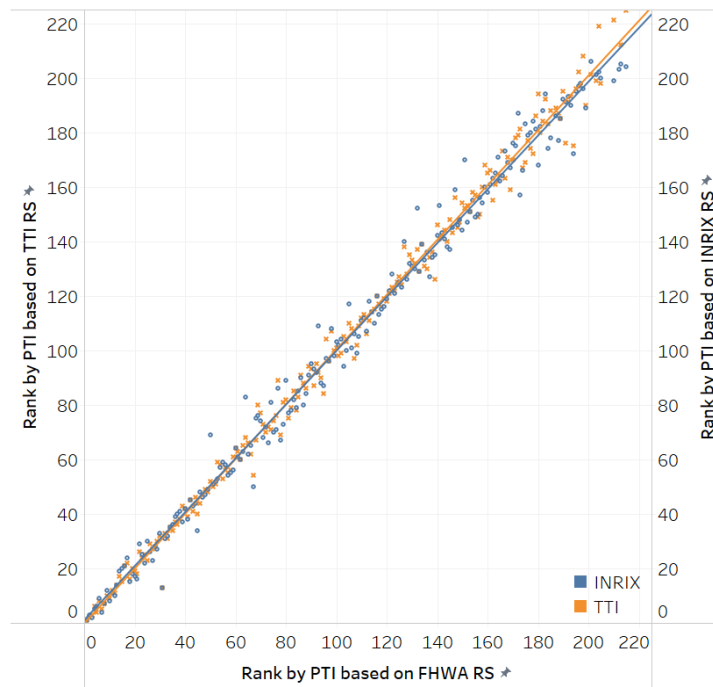
Transportation agencies often use a threshold of PTI value to identify unreliable travel times. A threshold of  $PTI > 1.5$  is used in this study to define unreliable travel time. In the morning peak period of 2023, the number of unreliable segments was 235, 231, and 207 based on the PTI calculated with TTI, FHWA, and INRIX reference speeds, respectively. The unreliable segments identified through the two sets of PTIs are highly consistent. The results for the other time periods and years are similar. This marginal difference further supports the conclusion that the choice among FHWA, TTI, and INRIX reference speed has a negligible effect on PTI ranking and identification of unreliable segments.

Figure 10 compares the rankings of TMC segments based on PTI values in the a.m. peak hours of 2023, calculated using the three sets of reference speeds. From Figure 10a, the rankings of segments by PTI values can vary significantly depending on the reference speed used. This variance indicates that although the overall PTI values are highly correlated, the relative ranking of segments by PTI can differ. However, the rankings were generally consistent for those ranked very high (the most unreliable segments) or very low (the most reliable segments), as shown in Figure 10a. The large differences primarily occurred on segments that have no apparent reliability issues. Therefore, the differences in the three sets of PTIs do not impact the identification of the most unreliable segments. Figure 10b shows the rankings of the top 100 unreliable segments, with the trend lines illustrating the relationships between ranks by PTI relative to FHWA reference speed and the other two sets of PTI. The two trend lines overlap and are close to 45 degrees, which indicates that the rankings by the three sets of PTI were generally consistent for the top 100 unreliable segments.



(a) Ranks of All Studied Segments

(b) Ranks of Top 100 Unreliable Segments



(c) Ranks of Segments with PTI > 1.5

Figure 10. Scatter Plot of (a) Rankings of All Segments; (b) Top 100 Unreliable Segments; and (c) Segments with PTI Greater Than 1.5 for a.m. Peak Hours in 2023. FHWA = Federal Highway Administration; IRS = INRIX reference speed; PTI = Planning Time Index; RS = reference speed; TTI = Texas A&M Transportation Institute.

Table 11 compares the rankings of the top 20 most unreliable segments based on the PTIs from the three sets of reference speeds. The rankings are quite similar, with the top three most unreliable segments being identical and most rankings differing by only a few positions. Furthermore, the Kendall’s Tau was calculated for the rankings of the top 100 unreliable

segments by the three sets of PTIs. The pairwise comparison results show strong agreement among the rankings by the three approaches. These findings confirm that the three sets of reference speeds produce comparable results for screening segments with unreliable travel time.

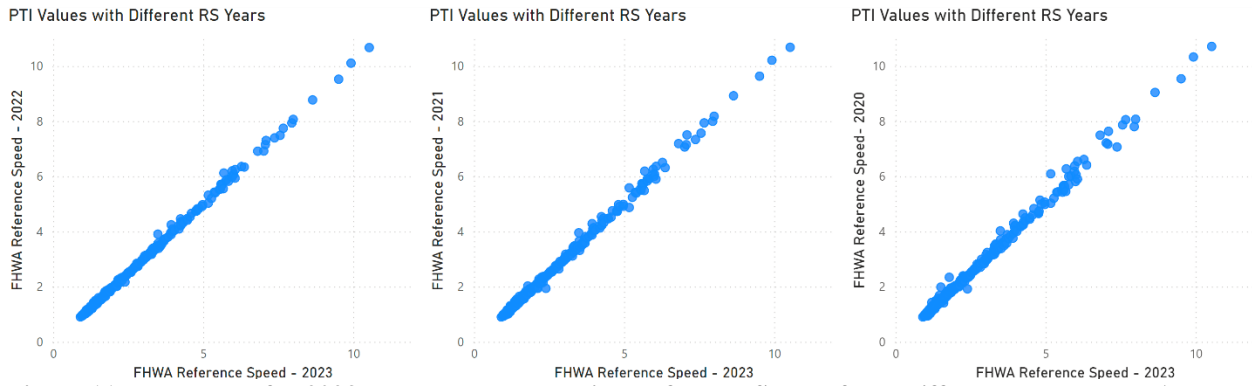
**Table 11. Comparison of Rankings of Top 20 Most Unreliable Segments**

<b>TMC Code</b>	<b>Rank by PTI Based on FHWA Reference Speed</b>	<b>Rank by PTI Based on TTI Reference Speed</b>	<b>Rank by PTI Based on INRIX Reference Speed</b>
110-04879	1	1	1
110N04879	2	2	3
110P04670	3	3	2
110-04878	4	6	5
110+04129	5	4	6
110+04670	6	8	9
110P04129	7	5	4
110P04128	8	7	7
110P04690	9	10	12
110P14755	10	9	8
110N04880	11	12	11
110N04162	12	11	10
110P04150	13	14	14
110N04878	14	17	19
110N04876	15	15	20
110P04855	16	21	21
110P04691	17	22	24
110P04610	18	16	15
110P04609	19	20	18
110+04610	20	16	17

FHWA = Federal Highway Administration; PTI = Planning Time Index; TMC = Traffic Message Channel; TTI = Texas A&M Transportation Institute.

### **Impact of Year-to-Year Reference Speed Variations on PTI**

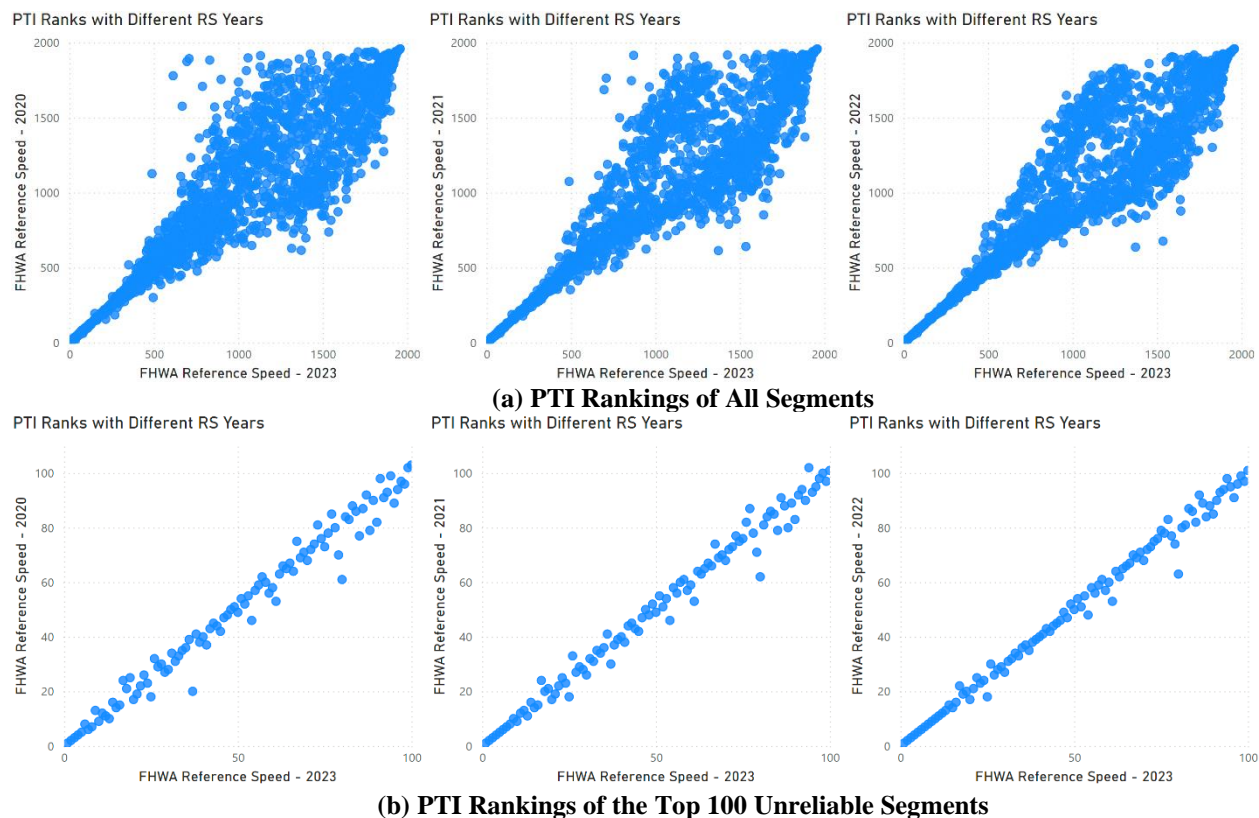
To evaluate the impact of reference speeds from different years on PTI, this study examines PTIs for a.m. peak hours in 2023 calculated using reference speeds from the years 2020, 2021, 2022, and 2023, respectively. Figure 11 shows the scatter plots comparing these PTI values based on FHWA reference speed. The trends observed for PTI calculated using TTI and INRIX reference speeds show a high degree of similarity and are therefore not included.



**Figure 11. PTI Values for 2023 a.m. Peak Hours Using Reference Speeds from Different Years. FHWA = Federal Highway Administration; PTI = Planning Time Index; RS = reference speed.**

The PTI calculated using reference speed from 2020 to 2022 demonstrates a high degree of correlation with the PTI values based on 2023 reference speeds. The correlation coefficients between PTI values using 2020, 2021, and 2022 reference speeds and those using 2023 reference speeds were 0.9886, 0.9916, and 0.9948, respectively.

Figure 12a shows the comparison of the ranking of segments based on PTIs calculated using FHWA reference speed for each study year. The results indicated a pattern similar to that observed in Figure 10a. Although the ranking of all TMC segments can be different when using reference speeds from different years, the rankings of the top 100 unreliable segments are quite similar, as shown in Figure 12b. The result suggests that, although there is variability in the rankings, the most unreliable segments identified are generally consistent. One potential explanation is that the average differences in reference speeds across the years are relatively small, and the PTI value is primarily influenced by the 95th-percentile travel time, especially for unreliable segments.



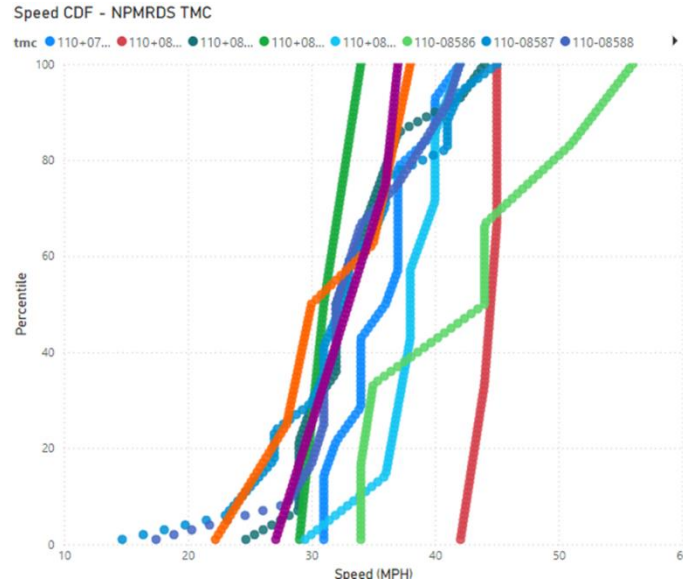
**Figure 12. Comparison of the Rankings of (a) All Segments and (b) the Top 100 Unreliable Segments by PTI Calculated Using Reference Speeds of Different Years. FHWA = Federal Highway Administration; PTI = Planning Time Index; RS = reference speed.**

## Exploration of Factors Affecting Reference Speed on Arterials

### Distributions of NPMRDS and INRIX Speeds

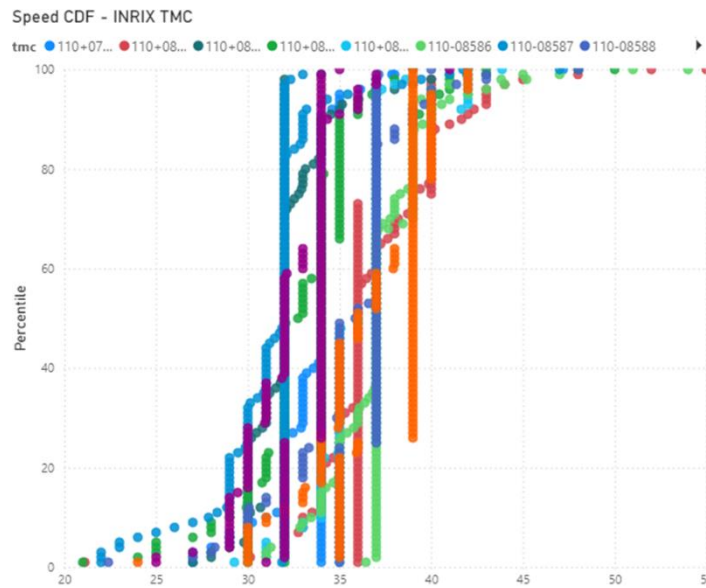
This section focuses on the analysis of speed cumulative distribution function (CDF) curves, derived from both the NPMRDS and INRIX datasets, for a sample of the same eight arterial segments with an AADT of around 1,500 and a PSL of 55 mph, collected during nighttime hours (Monday–Friday, 10 p.m.–6 a.m.). Although data availability analysis was conducted with the dataset, data screening based on data availability was not performed for this section. Filtering by data availability may be less practical in real-world applications by the practitioners due to the additional effort required. In contrast, utilizing factors such as AADT and TMC length, which are readily available and can be easily conflated onto the TMC network, is more feasible. Therefore, this section analyzes the data without applying data availability filters but instead includes discussions on AADT.

In Figure 13, derived from the NPMRDS, the CDF curves display notable variability across percentiles. The lack of smoothness is primarily due to the limited data availability in NPMRDS during off-peak hours, resulting in a lower sample size and, consequently, more jagged curves. When fewer data points are available, the CDF curves become more sensitive to individual data fluctuations.



**Figure 13. Speed CDF Curves from NPMRDS for Sample Arterial TMCs. CDF = cumulative distribution function; MPH = miles per hour; NPMRDS = National Performance Management Research Data Set; TMC = Traffic Message Channel.**

Figure 14, showing the speed CDF curves derived from the INRIX dataset for the same TMC segments and time periods, demonstrates a smoother and more consistent pattern. The difference is likely influenced by two main factors: a higher data availability in INRIX, leading to a larger sample size, and INRIX’s built-in data processing methods. INRIX’s data processing may include smoothing techniques or extreme value removal processes, reducing the likelihood of capturing outlier speeds and resulting in a more stable distribution. As a result, the CDF curves from INRIX appear less affected by sharp variations compared with the NPMRDS curves.



**Figure 14. Speed CDF Curves from INRIX Dataset for Sample Arterial TMCs. CDF = cumulative distribution function; TMC = Traffic Message Channel.**

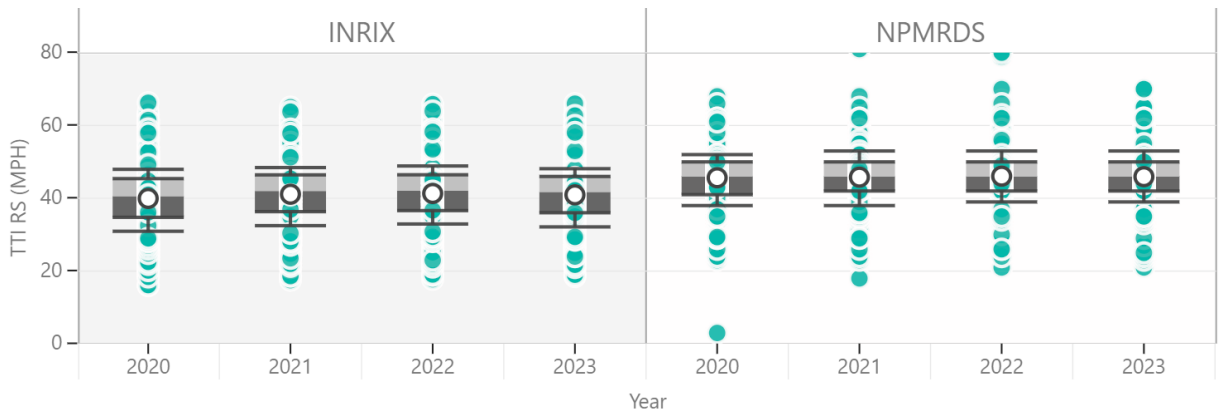
This comparison illustrates how differences in sample size and processing approaches between the datasets impact the reliability and interpretability of speed CDF curves. With lower data availability and limited built-in smoothing, NPMRDS data reflect a more fluctuating distribution, whereas INRIX provides a more stable representation. These distinctions highlight the importance of considering both data availability and processing techniques when using probe datasets to estimate reference speed on arterial segments, particularly under low-traffic conditions.

### **Arterial Reference Speed Estimates and Factors Affecting Reference Speed**

#### *Comparison of Reference Speed Estimates Between INRIX Dataset and NPMRDS*

This section compares reference speed estimates derived from the INRIX dataset and NPMRDS for arterial segments based on the 85th-percentile-based approaches—the FHWA and the TTI methods.

Figures 15 to 17 present reference speed estimates, in miles per hour, by year and data source (INRIX and NPMRDS) from the years 2020 to 2023 for all TMCs, with sub-figures (a) and (b) showing results from the TTI and FHWA methods, respectively. Each box plot illustrates the distribution of reference speed estimates derived from the two datasets for the same arterial segments. Figure 15 includes all arterial TMCs, Figure 16 shows the results after excluding short TMCs under 0.5 miles. Figure 17 further narrows the analysis by excluding TMC segments with an AADT below 30,000, allowing for a more focused comparison of higher-volume segments.

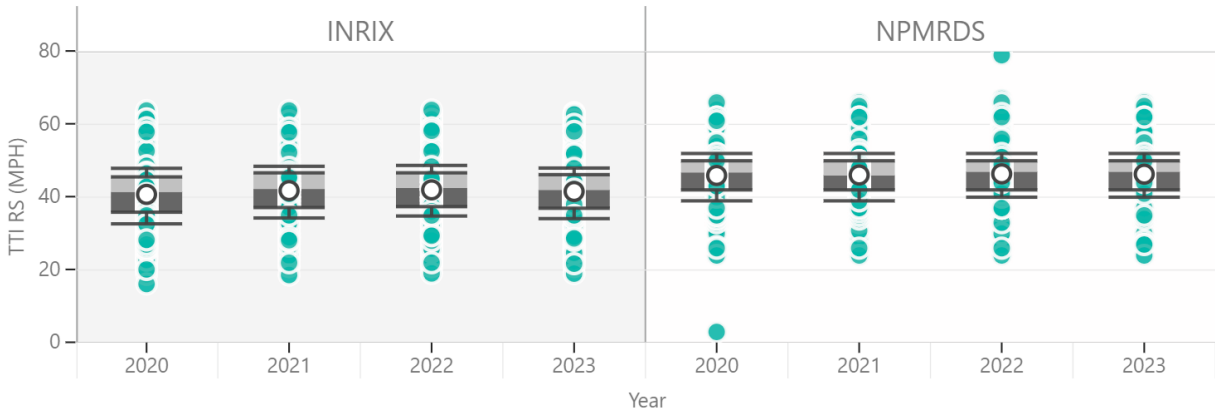


(a) Reference Speed Estimates Using the TTI Method

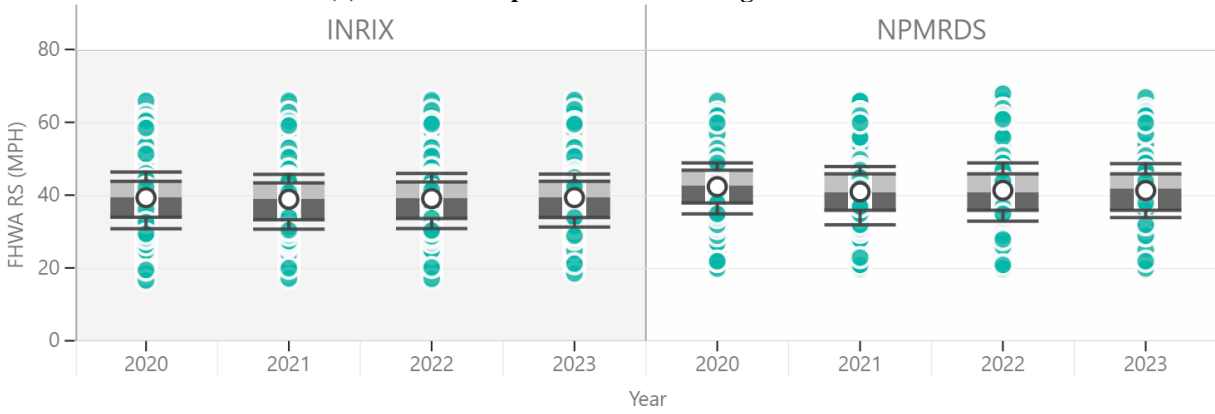


(b) Reference Speed Estimates Using the FHWA Method

**Figure 15. Reference Speed Estimates by Year and Data Source (All TMCs) using (a) TTI and (b) FHWA Methods ( $n = 5,181$ ). FHWA = Federal Highway Administration; MPH = miles per hour; NPMRDS = National Performance Management Research Data Set; RS = reference speed; TTI = Texas A&M Transportation Institute.**

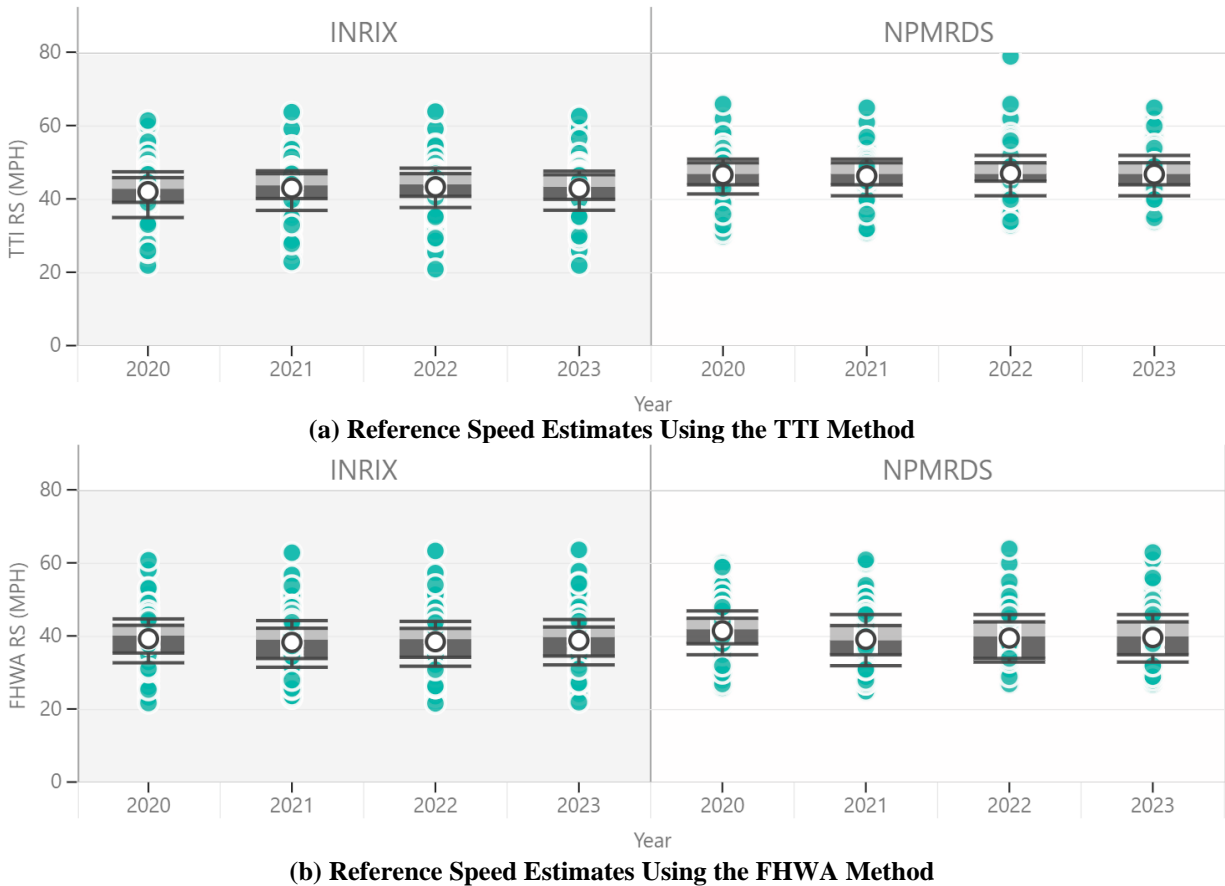


**(a) Reference Speed Estimates Using the TTI Method**



**(b) Reference Speed Estimates Using the FHWA Method**

**Figure 16. Reference Speed Estimates by Year and Data Source (Excluding TMCs Under 0.5 Miles) using (a) TTI and (b) FHWA methods (RS: Reference Speed) ( $n = 2,692$ ). FHWA = Federal Highway Administration; MPH = miles per hour; NPMRDS = National Performance Management Research Data Set; RS = reference speed; TTI = Texas A&M Transportation Institute.**



**Figure 17. Reference Speed Estimates by Year and Data Source (Excluding TMCs Under 0.5 Miles and AADT Less Than 30,000) using (a) TTI and (b) FHWA methods ( $n = 814$ ). FHWA = Federal Highway Administration; MPH = miles per hour; NPMRDS = National Performance Management Research Data Set; RS = reference speed; TTI = Texas A&M Transportation Institute.**

When comparing the box plots from the INRIX dataset (left side) with those from the NPMRDS (right side), it can be observed that although both datasets show minimal variation in median, mean, and interquartile ranges across the years, the spread of values and presence of outliers are more pronounced in the NPMRDS.

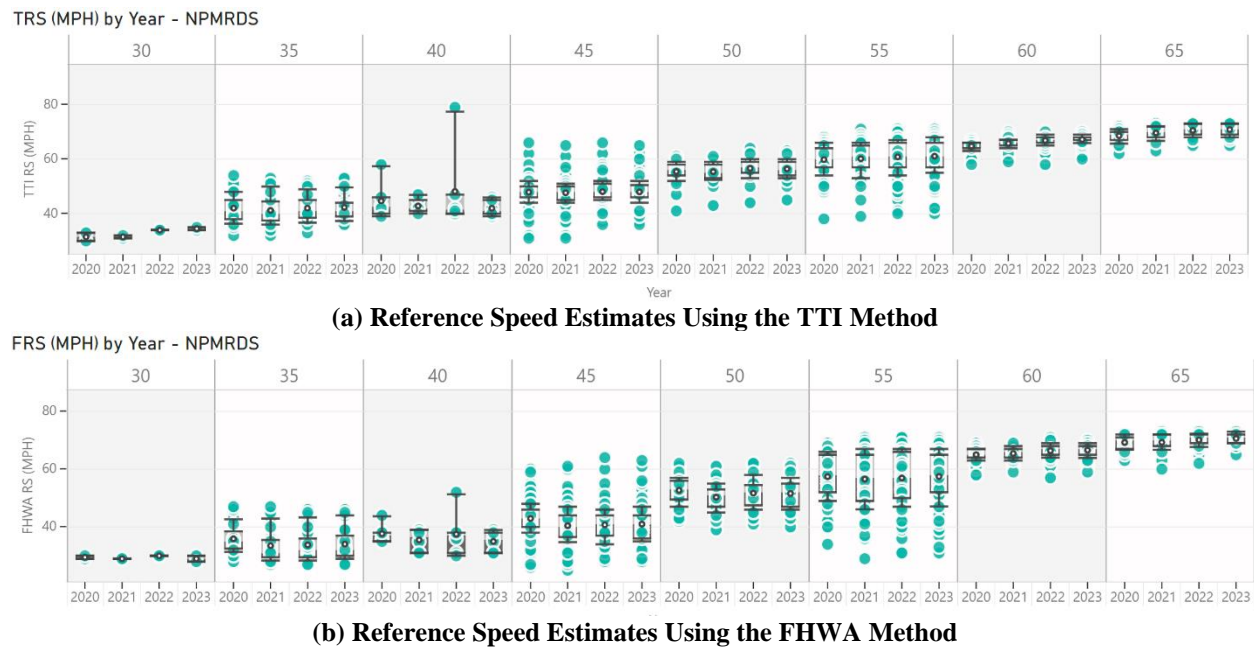
Figure 16, which excludes TMCs under 0.5 miles, shows a reduction in variability for both datasets, particularly for NPMRDS. With shorter segments removed, the NPMRDS still displays a wider spread and occasional outliers, albeit less extreme than in Figure 15.

Figure 17 further narrows the analysis by excluding TMCs under 0.5 miles and those with AADT less than 30,000. The resulting reference speed estimates show even greater stability, especially in the NPMRDS. The additional removal of low-AADT segments further reduces outliers and narrows the spread of values, bringing the two distributions closer together.

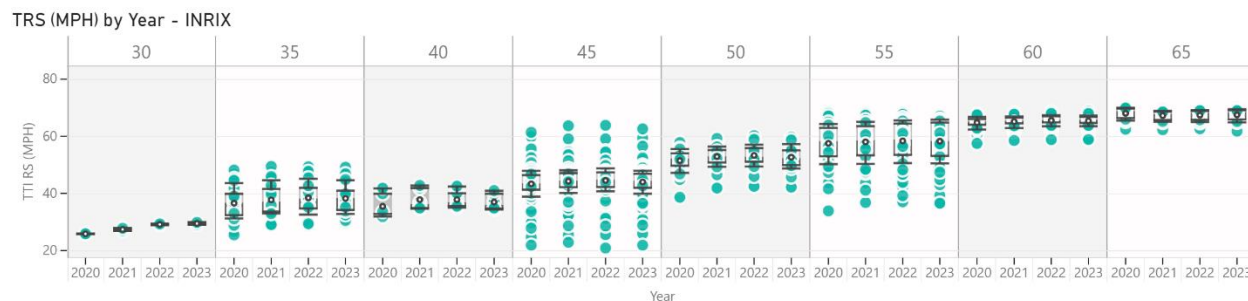
## Influence of Posted Speed Limit on Arterial Reference Speed

This section explores the relationship between PSL and reference speed on arterial segments. Reference speeds were calculated using both FHWA and TTI methods, whereas arterial segments were grouped by their PSLs, with PSL ranges from 30 to 65 mph in 5-mph increments to observe patterns across different speed limits. The number of observations for each PSL category is as follows: 30 mph (16 observations), 35 mph (122), 40 mph (33), 45 mph (512), 50 mph (77), 55 mph (865), 60 mph (403), and 65 mph (147). Note that the sum of all observations does not equal the total number of arterial TMCs, as some TMCs were not associated with a PSL, and short TMCs under 0.5 miles or those within intersections were removed from the analysis.

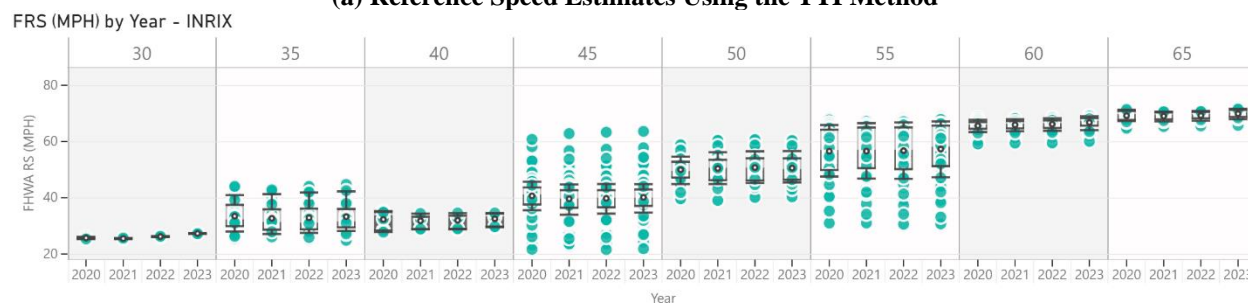
Figures 18 and 19 illustrate the distributions of reference speed for each PSL category during the years. Figure 18 shows reference speed estimates for the NPMRDS, with Figure 18a showing the result using the TTI method and Figure 18b using the FHWA method. Figure 19 presents the same analysis for the INRIX dataset, again with Figure 19a the TTI method and Figure 19b the FHWA method. Each box plot displays the spread of reference speed values within each PSL range, with the whisker indicating the 15th- and the 85th-percentile values.



**Figure 18. Reference Speed Estimates by Posted Speed Limit and Year with NPMRDS Using (a) TTI and (b) FHWA Methods. FHWA = Federal Highway Administration; FRS = FHWA reference speed; MPH = miles per hour; NPMRDS = National Performance Management Research Data Set; RS = reference speed; TRS = TTI reference speed; TTI = Texas A&M Transportation Institute.**



(a) Reference Speed Estimates Using the TTI Method



(b) Reference Speed Estimates Using the FHWA Method

**Figure 19. Reference Speed Estimates by Posted Speed Limit and Year with INRIX Dataset Using (a) TTI and (b) FHWA Methods. FHWA = Federal Highway Administration; FRS = FHWA reference speed; MPH = miles per hour; TRS = TTI reference speed; RS = reference speed; TTI = Texas A&M Transportation Institute.**

The trend of reference speed across different PSLs in Figures 18 and 19 demonstrates a clear positive relationship between PSL and reference speed. As PSL increases, the median and overall distribution of reference speed values also tend to rise, indicating that segments with higher PSL generally have higher reference speed, similar to patterns observed on the interstate network. This trend is consistent across both datasets, both methods, and all years from 2020 to 2023.

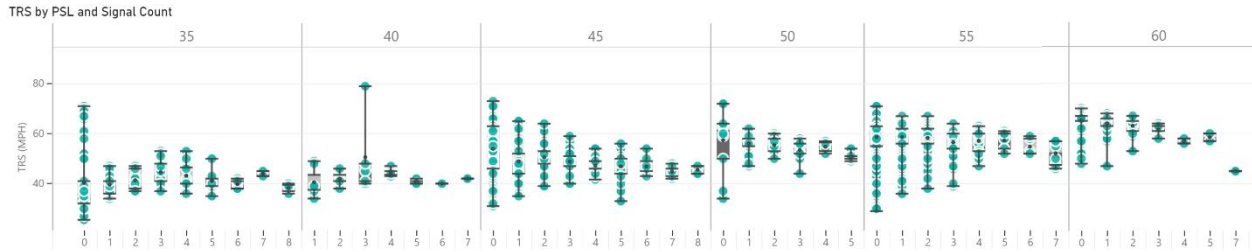
Both datasets show a wider spread in reference speed values on segments with PSLs of 45, 50, and 55 mph. This increased variability may be attributed to differences in roadway characteristics on these arterial segments, suggesting that additional analysis of other influencing factors may be warranted.

### *Impact of Traffic Signals on Arterial Reference Speed*

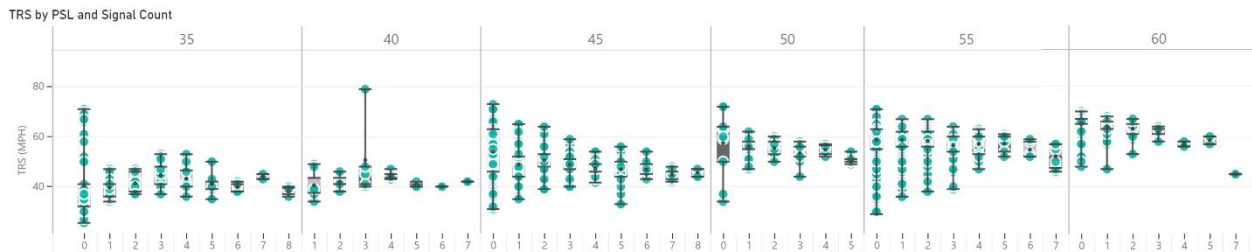
Following the PSL impact analysis in the previous section, this section examines how the count of traffic signals affects reference speed on arterial segments, as signals are expected to significantly influence traffic speed and are a defining feature that distinguishes arterial roads from interstates or other limited access facilities.

In this analysis, reference speed values for arterial TMCs with a varying number of signals along each segment were examined using data from the INRIX dataset from 2020 to 2023. Figure 20 shows the comparison of reference speed values across TMCs with different signal counts, segmented by PSL, using both the TTI and FHWA methods. Figure 20a presents the TTI method results, and Figure 20b shows the FHWA method results. Each subplot

represents a specific PSL category, ranging from 35 to 60 mph, with the x-axis indicating the number of signals along each TMC segment. The dots represent reference speed values for individual TMCs, and the whiskers in each box plot represent the 15th- and 85th-percentile values. The average TMC length is generally similar across different signal counts, ranging between 1.82 and 2.73 miles, as shown in Table 12. However, the maximum TMC length varies significantly across signal counts, with some TMCs extending up to 12 miles.



(a) Reference Speed Estimates Using the TTI Method



(b) Reference Speed Estimates Using the FHWA Method

**Figure 20. Impact of Traffic Signal Counts on Reference Speed by Posted Speed Limit Using (a) TTI and (b) FHWA Methods. FHWA = Federal Highway Administration; FRS = Federal Highway Administration reference speed; MPH = miles per hour; PSL = posted speed limit; TRS = TTI reference speed; TTI = Texas A&M Transportation Institute.**

**Table 12. TMC Segment Length by Signal Count on the Study Arterial Network**

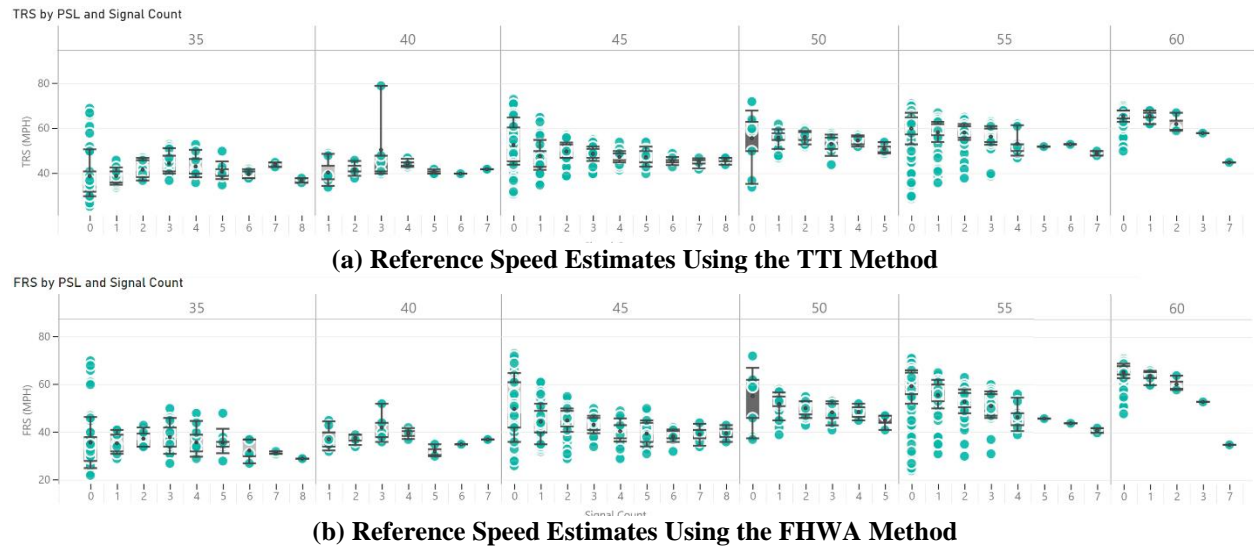
Signal Count	Average Length (miles)	Max Length (miles)	Min Length (miles)
0	2.47	12.00	0.5
1	2.73	11.66	0.5
2	2.22	10.42	0.51
3	1.82	11.31	0.53
4	1.83	7.57	0.51
5	2.05	5.29	0.56
6	2.57	11.87	0.85
7	2.40	4.21	1.41
8	2.04	2.32	1.83

Max = maximum; Min = minimum.

Figure 20 reveals a downward trend in reference speed as the number of signals along a TMC segment increases. Notably, TMCs with zero signal counts exhibit the highest variation in reference speed. In addition to lowering reference speed, an increased signal count also tends to reduce the occurrence of outlier reference speed values, reflecting the stabilizing impact of signals on speed variability. One potential explanation for this stabilizing impact is that traffic

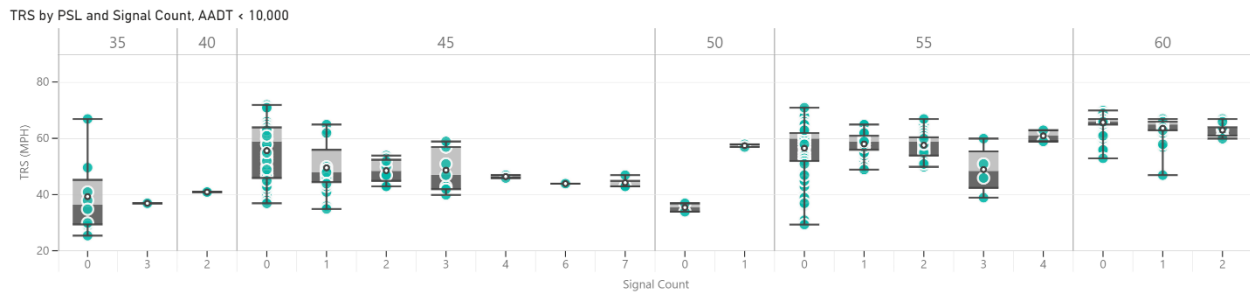
signals control the flow of vehicles and regulate their progression through the TMC. With multiple signals along a segment, travel times become more uniform as traffic is paced by the signals, reducing the likelihood of extreme speed variations.

To investigate whether TMC length impacts the relationship between signal count and reference speed, Figure 21 shows the reference speed by PSL, and signal counts for TMCs less than 2 miles long. Figure 21a presents the TTI method results, and Figure 21b shows the FHWA method results. The analysis in Figure 21 reveals that even when limited to shorter TMCs, the previously observed trend remains consistent. This trend also holds for TMCs longer than 2 miles, although the corresponding figure is not shown here.

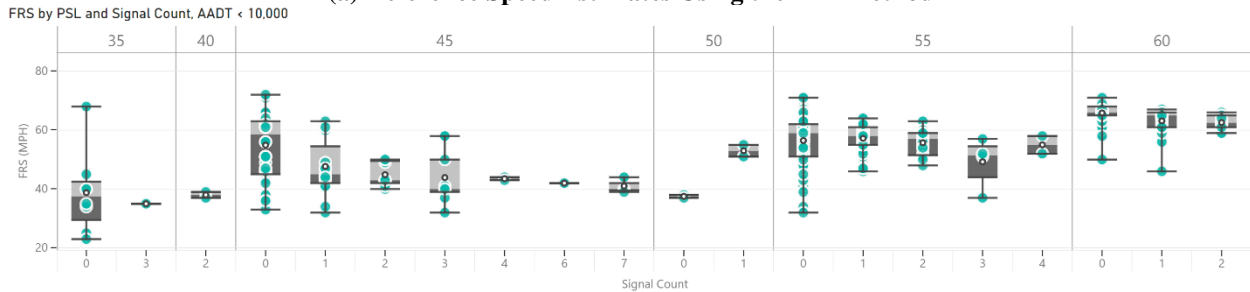


**Figure 21. Impact of Traffic Signal Counts on Reference Speed by Posted Speed Limit on TMCs Less Than 2 Miles Long using (a) TTI and (b) FHWA methods. FHWA = Federal Highway Administration; FRS = FHWA reference speed; MPH = miles per hour; PSL = posted speed limit; TMC = Traffic Message Channel; TRS = TTI reference speed; TTI = Texas A&M Transportation Institute.**

To further explore the impact, the data were divided based on high and low AADT values, using a threshold of 10,000. Figure 22 shows reference speed values by PSL and signal counts for segments with AADT below 10,000, and Figure 23 presents the same analysis for segments with AADT greater than or equal to 10,000. The number of observations for each PSL category with AADT threshold as 10,000 is as follows: 35 mph (10 observations with AADT less than 10,000/112 observations with AADT more than 10,000), 40 mph (2/31), 45 mph (87/425), 50 mph (4/73), 55 mph (319/546), 60 mph (176/227).

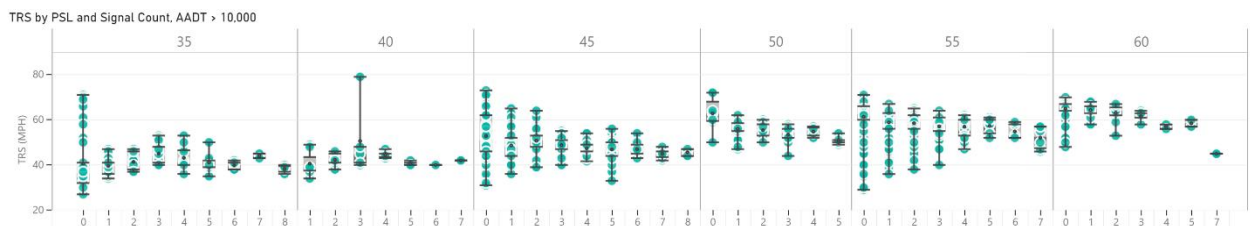


(a) Reference Speed Estimates Using the TTI Method

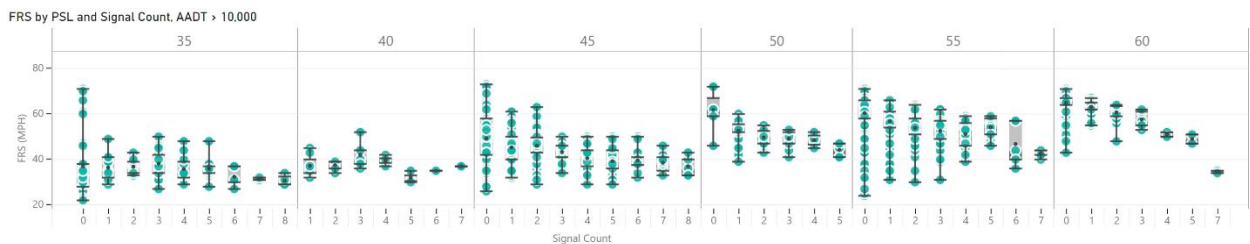


(b) Reference Speed Estimates Using the FHWA Method

**Figure 22. Reference Speed by Posted Speed Limit and Signal Count for Arterials with AADT Less Than 10,000 Using (a) TTI and (b) FHWA Methods. AADT = Average Annual Daily Traffic; FHWA = Federal Highway Administration; FRS = FHWA reference speed; MPH = miles per hour; PSL = posted speed limit; TRS = TTI reference speed; TTI = Texas A&M Transportation Institute.**



(a) Reference Speed Estimates Using the TTI Method



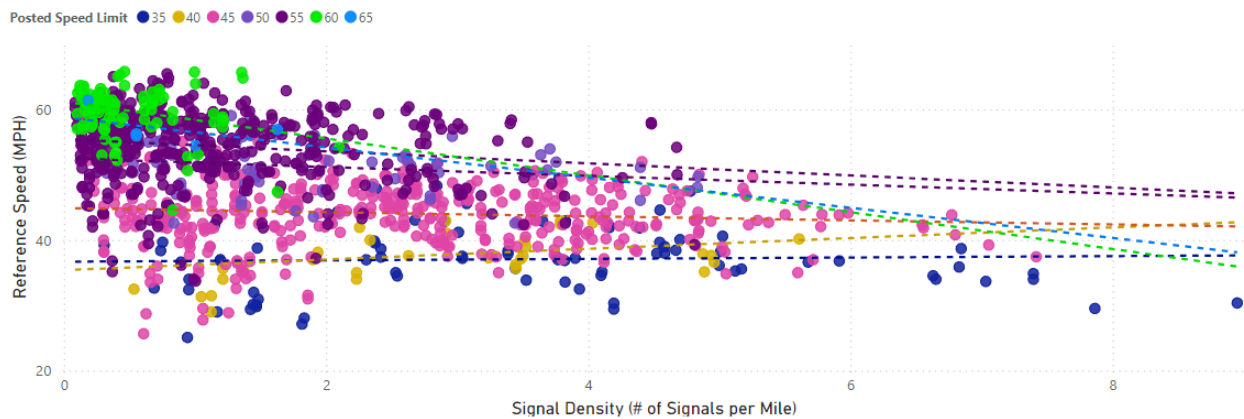
(b) Reference Speed Estimates Using the FHWA Method

**Figure 23. Reference Speed by Posted Speed Limit and Signal Count for Arterials with an AADT of More Than 10000 Using (a) TTI and (b) FHWA Methods. AADT = Average Annual Daily Traffic; FHWA = Federal Highway Administration; FRS = FHWA reference speed; MPH = miles per hour; PSL = posted speed limit; TRS = TTI reference speed; TTI = Texas A&M Transportation Institute.**

In the lower AADT group (Figure 22), reference speed tends to be less affected by signal count. In contrast, the higher AADT group (Figure 23) shows a more pronounced impact of signal count on reference speed, especially in higher PSL categories. This difference may be due to operational variations in traffic signal systems on lower versus higher AADT roads during

nighttime periods. Some signals may operate as independent intersections without coordination with the upstream and downstream signals, and others may function in coordination to manage heavier traffic flows. However, this assumption still needs to be validated through further study.

To further explore the impact of signal density, measured as the number of signals per mile, Figure 24 examines the relationship between signal density and reference speed across PSLs. As signal density increases, a general downward trend occurs in reference speed, suggesting that segments with higher signal density tend to have lower reference speeds. This trend is more relevant in higher PSL categories but is less evident for lower PSL categories (e.g., 35 and 40 mph). At lower signal densities (fewer signals per mile), reference speeds are generally higher, reflecting fewer interruptions and allowing for higher traffic speeds. However, as signal density increases, reference speeds start to decline as drivers encounter more frequent stops. The variability may also result from differences in signal timing, coordination, side street traffic demands, and intersection design, which warrant further exploration.



**Figure 24. Relationship Between Signal Density and Reference Speed Across Posted Speed Limits. MPH = miles per hour.**

In summary, both signal count and signal density seem to contribute to the reduction in reference speed on arterial segments. However, the high variability in reference speed estimates suggests that these two factors alone may not fully capture all influences, and further analysis incorporating additional factors is needed. However, adding more factors will reduce the sample sizes within each category, potentially limiting the robustness of the findings. As seen in Figure 21, the current factors already reduce sample sizes, with some categories containing only a few samples. Therefore, finding a balance between the number of factors considered and the sample size is crucial for a comprehensive analysis.

## Discussion

### Reference Speed for Interstates

For calculating mobility measures, a reference speed or travel time is often used to represent the performance in uncongested or free-flow conditions. Various methods have been developed to estimate reference speed. One common approach involves analyzing the distributions of traffic speeds during off-peak hours, using continuously collected data to capture the average speed when congestion is minimal. Another method often adopted by many agencies is to estimate reference speed using PSL. For interstate highways, the analysis using both NPMRDS and INRIX data from different years shows that the various reference speed definitions based on the 85th percentile of average segment speeds in low-volume conditions are highly correlated. The comparisons of reference speed from FHWA, TTI, and Jha methods show that the differences between the two sets of references are within a small range. This finding indicates a general consistency among the three methods. The FHWA method tends to produce higher reference speed compared with the TTI method for TMC segments with higher PSLs.

PSL (or PSL plus 5 mph) and the reference speed based on the 95th-percentile speed show low correlations with those based on the 85th-percentile speed. This finding is consistent with the consensus in the literature to use the 85th-percentile speed in low-volume conditions as free-flow speed for interstate highways. Reference speeds based on the 85th-percentile speed are generally higher than PSL, but the difference decreases for segments with higher PSLs. Although the reference speeds derived from FHWA and Jha methods were around 5 mph higher than PSL for segments with a PSL of 65 mph, using PSL plus 5 mph as reference speed is inconsistent with the other reference speed methods for segments of other PSLs.

### Congestion Threshold

The selected congestion threshold significantly affects the calculated delay values and their rankings among segments, as demonstrated through comparisons at statewide, districtwide, and corridor levels. The magnitude of delay values and their relative ranking among the study segments can change significantly when different thresholds are used. The sensitivity to congestion threshold highlights the importance of careful considerations when establishing congestion criteria, as it directly affects the performance evaluation outcomes.

### Impact on Travel Time Reliability Measure

The differences between FHWA, TTI, and INRIX reference speeds do not show a significant impact on the PTI values and the rankings of most unreliable TMC segments. The unreliable segments identified using PTIs that are calculated based on the three sets of reference speeds are very similar, and the top 20 unreliable segments from the three approaches are highly consistent. This consistency in results suggests that very little difference in top-ranked segments occurs because of the choice of reference speed, and all three methods are equally effective in identifying unreliable segments in the interstate network. Therefore, both the FHWA and TTI methods could be considered robust for calculating PTI for the purpose of screening-level performance analysis.

## **Importance of Consistent Reference Speed Method**

Establishing consistent methods for performance measures is critical. The findings from this study demonstrate the importance of adopting consistent reference speed methods and congestion thresholds for calculating delay and reliability measures. Consensus approaches for mobility and reliability measures allow for fair comparisons of projects in different geographical areas. Without a common benchmark, projects evaluated using measures calculated on an unequal basis would result in incomparable assessments. Differences in reference speed and congestion thresholds can lead to significantly varied outcomes, potentially skewing project prioritization. For example, methods that produce higher reference speeds or excessively high delay thresholds might overestimate congestion, resulting in unwarranted prioritization of certain projects with a lot of minor congestion over others that may have more critical delay issues. Therefore, it is crucial for transportation agencies to carefully select a standardized approach that aligns with their analysis goals. A consistent approach provides a solid foundation for decisionmaking processes related to infrastructure improvements, traffic management strategies, and resource allocation aimed at enhancing overall transportation system performance. Consideration should also be given to the uses and audience of the performance measures.

## **Data Availability on Arterial Networks**

On Virginia's National Highway System arterial networks, data availability for the NPMRDS is lower than for the INRIX dataset, with the NPMRDS frequently reporting extreme speed values. The data availability issue is more pronounced on roadway segments with lower functional classes, lower AADT, and during nighttime hours. Using the NPMRDS without quality checks or preprocessing may result in unreasonable reference speed estimates and unreliable performance metrics.

## **Factors Affecting Arterial Reference Speed**

Several factors influencing reference speed on arterial segments were revealed. PSLs are positively correlated with reference speed, whereas the number of traffic signals on a segment has a negative correlation, generally lowering reference speed and reducing speed variability. In contrast, segments with no signals exhibit higher speed variability. This relationship between signal and reference speed holds for both short (under 2 miles) and longer TMC segments. In addition, higher signal density (signals per mile) is associated with lower reference speeds, particularly on higher PSL roads. However, many observations show substantial variability, making it challenging to precisely determine the influence of these factors. This highlights the need for further analysis that incorporates additional factors.

## **CONCLUSIONS**

- *Reference speed estimation using the 85th percentile of average segment speed in low-volume conditions yields reliable and consistent outcomes.* The correlations among reference speeds from the 85th-percentile approaches are significantly stronger than their correlations

with reference speeds based on the 95th-percentile speed or PSL. This 85th-percentile approach typically produces reference speeds above the PSL, with smaller discrepancies on interstates with higher PSLs.

- *The congestion threshold, which defines the speed considered as congestion, strongly influences delay values and ranking among segments at statewide, district, and corridor levels for interstates.* Patterns of delay magnitude and rankings are sensitive to threshold selection, and caution should be taken when comparing delay metrics across projects or regions to ensure fair assessments. This finding has not been evaluated on arterial networks.
- *Reference speeds from different 85th-percentile-based methods—whether using different time windows for defining low traffic volume periods or using data from different years—may vary and yield different PTI values. However, the resulting PTI rankings, particularly for top-ranked segments, remain robust on interstate networks.* This consistency in identifying the most unreliable segments in the highway network demonstrates the stability of using the 85th-percentile-based reference speed for developing reliability measures.
- *Influenced by various factors such as PSL, segment length, and the presence of traffic signals, reference speed on arterial segments exhibits high variations.* Moreover, these influencing factors vary significantly across segments, making it challenging to evaluate their impact. Further research is needed to comprehensively account for the impact of these influencing factors on arterial reference speed.

## RECOMMENDATIONS

1. *VDOT's Traffic Operations Division should adopt the 85th-percentile-based method to estimate reference speeds on interstate networks for calculating delay and reliability performance measures.* Although the TTI method is more computationally intensive than the others, because of its inclusion of mid-day data when nighttime data are insufficient, in practice, the choice of reference speed results in a negligible difference in rankings of delay and PTIs on the most problematic segments in the interstate network, particularly when datasets of high availability and completeness, such as the INRIX dataset, are used. In addition, both the TTI and FHWA methods provide similar reference speeds, giving practitioners the flexibility to choose either method. However, it is essential to avoid comparing results derived from different methods to maintain consistency with internal decisionmaking processes at VDOT and contribute to a more uniform understanding of highway performance across different regions.
2. *The Transportation Research Council should explore and develop a reference speed estimation method specifically for arterial performance measures.* Although factors such as PSLs and the presence of traffic signals are known to influence reference speed, the significant variations in reference speed on arterial segments make it challenging to apply current methods effectively for performance measurement applications. Further explorations are needed to enable VDOT to better understand the complex characteristics of arterial segments, providing more reliable data for traffic management needs.

## **IMPLEMENTATION AND BENEFITS**

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

### **Implementation**

Regarding Recommendation 1, within 6 months of the report's publication, the Traffic Operations Division and Virginia Transportation Research Council will hold a stakeholder meeting to share the findings from this research and gather stakeholder feedback to guide implementation. Stakeholders should be identified in consultation with the Technical Review Panel of this study, which may include staff who often work on reference speed and performance measures, especially those in the Traffic Operations Division, Transportation and Mobility Planning Division, and Office of Intermodal Planning and Investment, as well as district offices. The meeting will cover key findings on probe datasets, interstate and arterial reference speeds, and their applications in performance measurement. In addition, feedback will be sought on (1) concerns related to calculating interstate reference speed and (2) insights regarding factors affecting arterial reference speeds.

Regarding Recommendation 2, by the end of 2024, the Traffic Operations Division will work with the Virginia Transportation Research Council to develop a research needs statement on reference speed estimation for arterial performance measurement and submit it to the Virginia Transportation Research Council System Operations Research Advisory Committee.

### **Benefits**

The findings regarding reference speed, congestion threshold, and their impacts on mobility and reliability performance measures will help VDOT establish a consensus approach for performance measurement, thereby supporting investment and policy decision-making.

The implementation of Recommendation 1 will improve the accuracy, consistency, and interpretability of delay and reliability measures in VDOT's performance measurement activities. These improvements will support more accurate and consistent cost-effectiveness analyses, enable more transparent project prioritization, and facilitate better decisions on resource allocation. Furthermore, the refined performance measures will strengthen the SMART SCALE program by providing more reliable and consistent information for project evaluation and scoring. This information will ensure funding decisions are aligned with SMART SCALE's objectives of helping Virginia meet its most critical transportation needs using limited tax dollars.

The implementation of Recommendation 2 will develop a method and provide a set of reference speeds for application on the National Highway System arterials in Virginia. This

method will serve as a decision-support tool for VDOT, improving the accuracy and consistency of performance monitoring and reporting on these roadways.

## ACKNOWLEDGMENTS

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## REFERENCES

- California Department of Transportation (California DOT). *Mobility Performance Report, 2023*. <https://dot.ca.gov/programs/traffic-operations/mpr/quarterly>.
- Cambridge Systematics, Inc., Dowling Associates, Inc., System Metrics Group, Inc., and Texas Transportation Institute. *Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability*. Transportation Research Board, Washington, DC, 2008.
- Dowling, R., Ryus, P., Schroeder, B., Kyte, M., Creasey, T., Rouphail, N., Hajbabaie, A., and Rhoades, D. *Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual*. NCHRD Report 825. Transportation Research Board, Washington, DC, 2016.
- Federal Highway Administration (FHWA). *Urban Congestion Report*. U.S. Department of Transportation, Washington, DC, 2020. [https://ops.fhwa.dot.gov/perf\\_measurement/ucr/documentation.htm](https://ops.fhwa.dot.gov/perf_measurement/ucr/documentation.htm).
- Federal Highway Administration (FHWA). TPM Guidebook, 2024. <https://www.tpmttools.org/guidebook/>. Accessed October 28, 2024.
- Jha, K. Determining Reference Speed from Probe-Based Travel Speed Data. Master Thesis, Texas A&M University, 2017. <https://oaktrust.library.tamu.edu/items/9055d9df-189a-4c2f-9b81-cb96a33c430f>.
- Margiotta, R., Eisele, B., and Short, J. *Freight Performance Measure Approaches for Bottlenecks, Arterials, and Linking Volumes to Congestion Report*. Federal Highway Administration, U.S. Department of Transportation, 2015. <https://ops.fhwa.dot.gov/publications/fhwahop15033/fhwahop15033.pdf>.
- Minnesota Department of Transportation (Minnesota DOT). *2021 Congestion Report*. State of Minnesota, St. Paul, MN, 2022. <https://mndot.org/freeway-operations/reports.html>.

- National Performance Management Measures. 23 CFR Part 490. November 1, 2024.
- Peer, S., Koopmans, C., and Verhoef, E. Prediction of Travel Time Variability for Cost-Benefit Analysis. *Transportation Research Part A: Policy and Practice*, Vol. 46, No. 1, 2012, pp. 79–90.
- RITIS. NPMRDS Analytics Suite. <https://npmrds.ritis.org/analytics/>. Accessed September. 10, 2024.
- Schrank, D., Albert, L., Eisele, B., and Lomax, T. *2023 Urban Mobility Report*. Texas A&M Transportation Institute, 2024. <https://mobility.tamu.edu/umr/>
- Schuman, R., Jones, T., and Turner, S. National Performance Management Research Data Set (NPMRDS) Descriptive Metadata Document Revision 2.0. <https://npmrds.ritis.org/>. Accessed October 5, 2024.
- Transportation Research Board (TRB). *Highway Capacity Manual*, 7th edition. Transportation Research Board of the National Academy of Science, Engineering, and Medicine, 2022.
- Texas A&M Transportation Institute. *Analysis Procedures and Mobility Performance Measures: 100 Most Congested Texas Road Segments*. Texas Department of Transportation, 2023. <https://static.tti.tamu.edu/tti.tamu.edu/documents/TTI-2023-4.pdf>.
- Vander Laan, Z., and Zahedian, S. *The Eastern Transportation Coalition Probe Data Validation: HERE, INRIX and TomTom*. State of Vermont, 2021. <https://tetcoalition.org/wp-content/uploads/2015/02/ETC-Validation-Report-VT01-FINAL.pdf>.
- Virginia Department of Transportation (VDOT). *Traffic Operations and Safety Analysis Manual (TOSAM) – Version 2.0*. State of Virginia, 2020. <https://www.vdot.virginia.gov/doing-business/technical-guidance-and-support/technical-guidance-documents/traffic-operations-and-safety-analysis-manual/>.
- Virginia Department of Transportation (VDOT). *2022 Operations Performance*. State of Virginia, 2023. [https://www.vdot.virginia.gov/media/vdotviriniagov/about/divisions/traffic-operations-division/2022-Operations-Annual-Report\\_acc1120223.pdf](https://www.vdot.virginia.gov/media/vdotviriniagov/about/divisions/traffic-operations-division/2022-Operations-Annual-Report_acc1120223.pdf).
- Washington Department of Transportation (Washington DOT). *Corridor Capacity Report*. State of Washington, 2018. <https://wsdot.wa.gov/publications/fulltext/graynotebook/corridor-capacity-report-18.pdf>.
- Williges, C., and Mahdavi, M. Transportation Benefit-Cost Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2079, No. 1, 2008, pp. 79–87.

- Wolniak, M., and Mahapatra, S. (2014). Data- and Performance-Based Congestion Management Approach for Maryland Highways. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2420, No. 1, 2014, pp. 23–32.
- Xu, J., and Lambert, J. Risk-Cost-Benefit Analysis for Transportation Corridors with Interval Uncertainties of Heterogeneous Data. *Risk Analysis*, Vol. 35, 2015, pp. 624–641.
- Zhang, X., and Chen, M. *Determining Reference Speed for Urban Arterials Using GPS-Based Speed Data*. The Transportation Research Board 94th Annual Meeting, Washington, DC, January 11–15, 2015.

## APPENDIX

This appendix describes the steps for calculating reference speed for Traffic Message Channel (TMC) segments, using either the Federal Highway Administration (FHWA) or Texas A&M Transportation Institute (TTI) method. The procedure involves six steps:

- Step 1: Determine the spatial scope and target year.
- Step 2: Obtain data for the study.
- Step 3: Create a dataset to include data for the time window defined by the FHWA or TTI method.
- Step 4: Organize the data in ascending order.
- Step 5: Calculate the index for the 85th percentile of each TMC segment.
- Step 6: Determine the reference speed for each TMC segment.

Each step is described below.

### **Step 1: Determine the Spatial Scope and Target Year.**

- Define the spatial scope by selecting the TMC segments of interest.
- Identify the target year for analysis to ensure the dataset reflects the desired time period.

### **Step 2: Obtain Data for the Study.**

- Access the RITIS data portal using authorized credentials.
- Select the desired geographic area and time frame based on the spatial scope and target year.
- Export 15-minute aggregated speed data.

### **Step 3: Create a Dataset for the FHWA or TTI Time Window.**

Use one of the following methods to filter the dataset for the desired time window:

#### **Step 3A: FHWA Reference Speed Method**

- Filter the 15-minute aggregated speed data to include only the off-peak periods defined below:
  - Weekdays: 9:00 a.m. to 4:00 p.m. and 7:00 p.m. to 10:00 p.m.
  - Weekends: 6:00 a.m. to 10:00 p.m.

#### **Step 3B: TTI Reference Speed Method**

- Filter the 15-minute aggregated speed data to include the following periods:
  - Weekdays: Overnight (10:00 p.m. to 6:00 a.m.).
- Determine if fewer than one-half of the overnight periods during weekdays are populated:
  - Count the total number of possible 15-minute time intervals in the overnight period for the target year.
    - ❖ Each overnight period has 32 intervals (8 hours × 4 intervals per hour).

- ❖ Multiply by the number of weekdays in the year (e.g., 261 weekdays for a non-leap year).
- ❖ Total intervals =  $32 \times 261 = 8,352$ .
- Count the number of populated (non-missing) speed values in the dataset for these intervals.
- If the number of populated values is less than one-half of the total intervals ( $8,352 \div 2 = 4,176$ ), then supplement the dataset with mid-day speeds:
  - ❖ Supplement the dataset if fewer than one-half of the overnight periods are populated:
    - ✓ Include speeds from the weekday mid-day period (11:00 a.m. to 4:00 p.m.), which consists of 20 intervals per day (5 hours  $\times$  4 intervals per hour).
    - ✓ Combine the overnight and mid-day speeds into a single dataset for further analysis.

**Step 4: Sort the Speed Data in Ascending Order.**

- For each TMC segment, arrange the 15-minute speed values in the dataset from the lowest to the highest speed.

**Step 5: Calculate the Index for the 85th Percentile.**

- Use the following equation to determine the index position of the 85th percentile of a TMC segment in the sorted dataset:

$$P = \frac{N + 1}{100} \times k$$

where:

$P$  = Index position of the 85th percentile.

$N$  = Total number of data points for the TMC segment in the dataset.

$k$  = Desired percentile ( $k = 85$ ).

**Step 6: Determine the Reference Speed.**

- If  $P$  is a whole number, the 85th-percentile speed is the speed at that index position in the sorted dataset.
- If  $P$  is not a whole number, round  $P$  up to the nearest whole number and use the corresponding speed value at that index as the 85th-percentile speed.
- Use the 85th-percentile speed of each TMC as its reference speed.