



Considerations for Calculating Arterial System Performance Measures In Virginia

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RAMKUMAR VENKATANARAYANA, Ph.D.
Research Scientist

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<p>16. Abstract:</p> <p>The Moving Ahead for Progress in the 21st Century Act (MAP-21) mandates that state departments of transportation monitor and report performance measures in several areas. System performance measures on the National Highway System (NHS) are part of the final MAP-21 rule making. The NHS includes both freeways and arterials. However, in comparison to freeways, arterial system performance measures have not been studied extensively until recently. In addition, the Virginia Department of Transportation (VDOT) business plan (FY 16) aims to improve arterial travel times and safety through increased performance monitoring and management. To support all these goals, this study investigated several measures, parameters, options, and factors that impact arterial system performance measure calculations. The study network in VDOT's Hampton Roads District included 288 directional miles of arterials with diverse attributes. The benchmark network consisted of 15 miles of roads and Bluetooth data.</p> <p>Measures studied included traffic delay, planning time index, travel time index, the American Association of State Highway and Transportation Officials reliability indexes (RI80, for all days and weekdays), congested hours, and congested miles. Eleven calculation parameters were studied, namely, data quantity and quality, data filtering, spatial segmentation, weighting factors, correlation among the measures, time-of-day traffic volume profiles, truck definition, time aggregation interval, congestion reference speed, congestion threshold, and peak period definition. For each parameter, a number of value options were studied. Four geometric and traffic factors were studied, namely, annual average daily traffic volumes, speed limit, signal density, and segment lengths. Given the large number of parameters, options, and factors, and the small benchmark network, this study focused on exploratory analyses rather than statistical significance tests.</p> <p>Key findings of the study include:</p> <ul style="list-style-type: none"> • Data from the National Performance Monitoring Research Data Set (NPMRDS) have less observable daily patterns and high day-to-day variability compared to Bluetooth and INRIX data. Data availability is low across all data sources during nighttime periods. • Even after data filtering, annual network delay errors were as high as -40% (INRIX) and +155% (NPMRDS) compared to the benchmark; errors in regional planning time index and 80th percentile reliability indexes (RI80) were below 15%, and travel time index error was less than 10%. All indices were highly correlated and were robust to changes in most parameter options, often changing less than 3%. • Volume profile methodologies and peak period definitions impact peak period vehicle miles traveled by more than 10%. Volume profiles and large spatial segments also impact delays by more than 10%. Changes in the definition of "truck," temporal aggregation options, and small changes in spatial segmentation hardly impacted delay. <p>Recommendations include:</p> <ul style="list-style-type: none"> • VDOT should calculate and monitor measures to gain more experience with the data, the network measures, and their trends; nighttime data are not prime for measures. • VDOT should study big data approaches and mobilize data storage and computational resources to analyze these large datasets. 			
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FINAL REPORT

**CONSIDERATIONS FOR CALCULATING ARTERIAL SYSTEM
PERFORMANCE MEASURES IN VIRGINIA**

Ramkumar Venkatanarayana, Ph.D.
Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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EXECUTIVE SUMMARY

Introduction

For the past several years, the Virginia Department of Transportation (VDOT) has been working to establish performance measures that provide internal and external indicators of system condition and level of service. This effort was underscored by the federal transportation legislation signed into law in July 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21). This legislation mandated that state departments of transportation monitor and report performance measures in several areas on a biennial basis including system performance measures for the National Highway System.

On April 22, 2016, the Federal Highway Administration posted a Notice of Proposed Rulemaking (NPRM) in the *Federal Register* (2016) to propose national performance management measure regulations to assess the performance of the National Highway System. The comment period ended August 20, 2016. In preparation for the NPRM and the comment period, VDOT initiated this study to understand better the issues relating to arterial system performance monitoring. In addition to informing the NPRM comment process, the VDOT Business Plan for Fiscal Year 16 (FY16) (VDOT, 2015) includes improving arterial travel times and safety through increased performance monitoring and management.

Although performance monitoring on freeways has been the subject of considerable work, arterial system performance measures have not been studied extensively until recently. This study assessed current data availability, identified potential system performance measures, calculated them for a study network using different calculation factors, analyzed the results for different geometric and traffic factors, and developed a number of recommendations.

Purpose and Scope

The purpose of this study was to support VDOT's efforts to comply with MAP-21 arterial system performance measurement and reporting mandates and assist VDOT in making more informed operations and resource allocation decisions. The word "arterial" is used in this report to mean any surface street that is not access controlled. This includes both signalized and unsignalized facilities.

The study had four objectives:

1. Identify candidate performance measures based on a review of current arterial congestion and system reliability performance measures used by other states and in previous studies.
2. Identify data needs to support VDOT's performance measurement and reporting, and inventory current VDOT data to identify additional data needs.

3. Develop guidance for segmenting the roadway network and weighting performance measures to calculate the aggregate measures at the corridor/network levels from data at the link/segment levels.
4. Study the effects of missing data (less than ideal data quality) and the definition of “truck” in terms of vehicle classes on the candidate performance measures.

The scope of the study was limited to congestion and system performance measures of arterial networks. The study used a 228-directional mile network from the Hampton Roads area, not the entire state.

The Mobility Measurement in Urban Transportation Pooled Fund Study is currently carrying out a synthesis project on arterial system performance measurement that addresses thresholds and target setting. The results of that study are expected to be practice-ready for VDOT.

Methods

Four main tasks were undertaken to achieve the study objectives:

1. A literature survey was conducted to identify potential performance measures for use in arterial performance monitoring, calculation methodologies, and factors influencing the measures such as threshold speeds for defining delay, spatial segmentation, data requirements and sources, and visualization approaches effective for communicating the performance measures. Then, performance measures considered appropriate for Virginia were selected in coordination with the project’s technical review panel and were carried through the remaining tasks.
2. For the performance measures selected in Task 1, the data required to calculate each measure were identified and available data in Virginia were inventoried. Gaps in data were specifically identified.
3. The performance measures selected were calculated for the study network and analyzed with regard to several factors, including volume profile method, truck definition, segment lengths, weighting methods, etc. The study network was defined in cooperation with the technical review panel. In the selection of the routes for the study network, the following diverse characteristics were considered that would allow results to be applicable to the rest of Virginia:
 - *National Highway System functional classes*: MAP-21 principal arterial, Strategic Highway Network (STRAHNET) route, STRAHNET connector, intermodal connector
 - *Traffic patterns*: urban/suburban/rural, recreational/seasonal, and commuter traffic

- *Number of lanes:* 2, 4, and 6 (both directions)
 - *Annual average daily traffic (AADT):* 2,100 to 73,000 (both directions)
 - *Truck percentage:* 1% to 17%
 - *Directional traffic (peak traffic percentage in peak direction):* 50% to 75%
 - *Speed limits:* 25 to 55 mph
 - *Corridor length:* 0.5 to 63 miles
 - *Signal density per mile:* 0 to 5 (considering link lengths of 1 mile or longer)
 - *Intersections:* signalized (coordinated and isolated), unsignalized, and grade-separated interchanges
 - *Other notable aspects of the selected network:* school speed zones, railroad crossings, end of freeway, and bridges.
4. Based on the results of the analyses performed in Task 3, recommendations were developed for calculating appropriate Virginia arterial performance measures.

Results and Discussion

An objective of the study was to develop prescriptive recommendations on calculating arterial system performance measures. However, because of the lack of data availability and the numerous parameter options, considerations instead of recommendations were developed, as listed in this section.

There is often no one simple answer with regard to the applicability of a particular option to a particular geographic area, time period of analysis, or purpose of measurement. At a minimum, in the selection of appropriate calculation parameter options, the tradeoffs across the following should be considered: (1) robustness of performance measures with regard to data quality and variability; (2) desired level of sensitivity and precision of performance measures with regard to VDOT actions; (3) purpose of the performance measure; and (4) analysis resources available (e.g., data availability and granularity, data storage, computational servers, and staff).

Considerations for Calculating Arterial System Performance Measures

These considerations were developed from a limited network and past data. The study network consisted of 288 directional miles of urban/suburban/rural arterials with nearly 500 signalized intersections. The benchmark network used for data quality analyses consisted of 15 directional miles within the study network. As a result, some considerations may not fully

transfer to a different network, such as one with heavy congestion in Northern Virginia. Transportation experts and probe data vendors alike expect data quality, availability, and coverage to keep improving over time, thus providing a more solid base for these performance measures.

- *The selection of a volume profile had a large impact on delays.* Compared to local continuous count station traffic volume profiles, the Texas A&M Transportation Institute’s *Urban Mobility Scorecard* (Schrank et al., 2015) profiles decreased INRIX-based study network delays by 11% and delay based on the National Performance Management Research Data Set (NPMRDS) by 2%. Network index measures were less than 1% different for both data sources. Although daily vehicle miles traveled (VMT) remained comparable between the two volume profile approaches across the different spatial levels of analyses (<0.08% difference), PM VMT was about –11% to –15% different. As expected, local traffic profiles had more diversity than the *Urban Mobility Scorecard* profiles.
- *The definition of “truck” in terms of vehicle classes had a minimal impact on results.* When “truck” was defined as Class 6 and above, network VMT was 0.75% less than when it was defined as Class 5 and above; INRIX-based delay was 3.2% less, and NPMRDS-based delay was 1% less. All index measures changed less than 0.5%.
- *The definition of the congestion reference speed impacted results.* Compared to daytime light traffic speed (LTS) (i.e., the average speed of the least congested 2 hours during the day), use of the INRIX reference speed as the free flow speed resulted in a regional delay increase of 51%. The index measures increased by 3.4% to 5.1%. All the measure values calculated using the INRIX reference speed and the posted speed limit (PSL) were comparable.
- *The length of the peak period had only minimal impacts on results.* Reducing each peak period by 2 hours impacted the planning time index and the travel time index by less than 1.5% using INRIX data and less than 2.7% using NPMRDS data.
- *The level of data aggregation had a minimal impact on the results.* Compared to 15-minute aggregated data, 1-hour aggregated data impacted INRIX-based measures by less than 0.8%, NPMRDS-based network delay by 12.4%, and NPMRDS-based index measures by less than 4%.
- *Spatial segmentation can have large impacts on results.* Compared to INRIX Traffic Message Channel segments, custom segments based on rules of thumb (such as homogeneous traffic volume, speed limit, number of lanes, signal density, etc.) decreased network delay by –3.4% and all the index measures by 0.7% to 1.9%. However, consideration of very long segments, such as the entire corridor in each direction, noticeably washed out congestion and decreased the delay by 29% and the index measures by 2.3% to 4.9%. The corresponding reductions using NPMRDS was 43% for delay and 5.7% to 9.5% for index measures.

- *Contrary to expectations, the various index measures across different parameter options had less than 2% difference when calculated using different weighting factors.* The main concern with this observation is that the network index measure may not be very sensitive to VDOT operational or traffic engineering actions at individual segments. As such, many VDOT actions may go unnoticed.
- *System performance measures depend on traffic demand and road capacity supply.* No noticeable patterns were observed between the studied measures and individual geometric and traffic factors such as AADT, segment length, signal density, and PSL. The highest R-squared value was between delay per mile and signal density at 0.5. All other R-squared values were less than 0.25 or even 0.1.
- *Congestion is a complex issue.* A single measure (e.g., congested miles) explains only one aspect of congestion. Monitoring multiple measures simultaneously (congested miles and congested hours) provides a more robust picture. As the congestion threshold increased, congested road miles increased in a monotonic, non-linear manner. However, VMT-weighted network congested hours did not vary monotonically, since newly congested segments with fewer hours and higher VMT can reduce network congested hours.

Additional Considerations

- *Weighting factors should be selected to differentiate truck and car measures.* In principle, if trucks are assumed to travel during the same times as cars and their proportions are similar on different roads, reliability measures for cars and trucks are expected to be similar and length weight is reasonable. If trucks are restricted in some locations, then using length weights after ignoring those road segments is more reasonable. If trucks travel at different times than cars or in different proportions on different road segments, then volume and VMT weights are more reasonable for differentiating system performance for cars and trucks. When delays and bottlenecks are inherently different between cars and trucks on a network, one would also expect differences in the reliability index, planning time index, and travel time index. Using truck volume or VMT as a weighting factor is expected to illuminate these differences better in principle even if not in calculated numbers.
- *The issue of data quality and quantity requires additional attention.* VDOT already uses segment level measures for Smart Scale evaluations and other analyses, such as before-after studies. However, network-level measures and annual monitoring are still relatively new concepts, especially for arterial systems. Considering the noticeable impacts of speed data quality and quantity on the network measures observed in this study, VDOT needs to gain more experience in this area. Further, during this period of gaining experience, VDOT needs to make a request to the Federal Highway Administration that it not apply penalties or tie appropriations to target achievement.

- *Congestion reference speed should be chosen with care.* There are advantages and challenges to using any of these three reference speeds: vendor-supplied reference speed, PSL, and daytime LTS. Vendor-supplied reference speeds can change over time, but the reasons for the changes are not documented. Some vendors, such as NPMRDS, do not provide reference speeds. PSL is available for state-maintained roads but not for city- or county-maintained roads. PSL and daytime LTS are comparable for freeways, and they both provide a desirable reference to capture total delays. However, by design, PSL is not achievable when traffic control devices are present. Therefore, if PSL is used as a reference, appropriate “acceptable congestion/delays” must also be developed and communicated to citizens and elected officials. Delay based on daytime LTS will be artificially low for severely congested roads, whether because of heavy traffic volume or inefficient signal timings.

For any one homogeneous segment, the congestion reference speed does not make much difference, because it is simply a reference line drawn to calculate delay and other measures. Only the magnitude of the measure will be affected. Depending on the use of the measure, such magnitude differences may be unimportant (such as for annual trend monitoring) or easily accounted for (such as prioritizing two similar segments for projects). However, network measures will be impacted in complex ways by the reference speed selected. With PSL, a downtown street may be shown to be much more congested than a suburban roadway. With daytime LTS, the opposite may be shown. For all these reasons, both PSL and daytime LTS are recommended for use in the near future in order for VDOT to gain further experience with their use.

- *More resources are needed to manage data and calculate measures.* Even for the small study network, calculations took about 4 hours to run completely on a standard issue VDOT laptop. Calculating these measures for the entire state of Virginia, even with optimized data flow, using personal computers and Statistical Analysis System software will take several days to complete. Cambridge Systematics, Inc. (2016) prepared a white paper on the step-by-step calculation procedures for the NPRM measures that identify higher resource needs. The white paper stated: “Calculating the performance measures in the proposed Part 490 would require more than a spreadsheet on a basic desktop computer”; it further documented specific requirements such as “capability for routinely storing and processing at least 5 to 10 terabytes of data” and “ideally, a server (with appropriate disk redundancy and system backup) dedicated to storing and processing very large data sets.” Further, Pack and Lund (2014) estimated that the emerging connected and automated vehicle paradigm will increase the traffic data availability and analytical needs by an order of magnitude beyond the probe data currently available. In recent years, international conferences such as the 2016 Annual Meeting of the Transportation Research Board and the 2016 North American Traffic Monitoring and Exposition Conference have also focused considerable attention on storage and analytical solutions to this emerging data explosion through a “big data” approach. Although not examined as a part of this study, big data approaches seem promising and even essential (Cambridge Systematics, Inc., 2016; Pack and Lund, 2014) for calculating statewide system

performance measures and actively managing the system (through conducting what-if analyses and finding root causes of problems).

Conclusions

- *Data availability should be sufficient for daytime analyses of the studied measures.* For the three data sources examined in this study, i.e., Bluetooth, INRIX, and NPMRDS, daytime (5 AM-10 PM) availability of filtered data was about 15% higher than availability for the whole day (34%-60%). Therefore, the data sets listed in Table ES1 are more suitable for analyzing recurring traffic congestion during daytime rather than nighttime work zones or special events.

Table ES1. Data Availability by Source, Time Period, and Filtering

Parameter	Bluetooth	INRIX	NPMRDS
Full day	-	98%	39%
Full day filtered	60%	47%	34%
Daytime (5 AM-10 PM) filtered	76%	61%	48%

- *Bluetooth and INRIX data have comparable day-to-day variability, whereas NPMRDS data have a much higher variability than both (with the 2013 data studied).* NPMRDS Traffic Message Channels examined in this study had much larger variations in both the raw data and the measures compared to Bluetooth and INRIX, even as the average speed profiles were comparable. Raw data were analyzed through visual assessments of daily speed profiles, cumulative frequency distributions, and standard deviations by time of day. Further, data filtering changed NPMRDS network delays by more than 40%, which is practically very high for annual system performance monitoring, target setting, and management. Significant improvements in NPMRDS data availability and quality are needed before the data are used for network delay performance monitoring.
- *Large amounts of missing data result in huge impacts to system performance measures.* Six months of missing data caused INRIX delay per mile for the benchmark network to decrease by 4.3%, whereas the same measure with Bluetooth data increased by 2.3%. Even though detailed and precise studies on the effect of missing data on measures could not be carried out, the presented observation emphasizes the need for attention in interpreting measures when large portions of data are missing.
- *Some performance measures can be reliably estimated from other measures.* This observation is especially pertinent if data quality or availability is not sufficient to calculate a specific measure directly. All index measures for each data source, irrespective of the weights, spatial resolution, time periods, and parameter options examined, were highly positively correlated. Most R-squared values were above 0.85. Most low correlations were found for the AM peak periods, which had lower congestion.

Recommendations

1. *The Virginia Transportation Research Council (VTRC) should use the detailed findings of this study to support VDOT's Traffic Engineering Division (TED) and Operations Division (OD) in developing comments on the system performance measures NPRM. This recommendation was carried out as a technical assistance (TA) project. The results of this study and a draft of this report were shared with VDOT's TED and OD.*
2. *VDOT's TED and OD should calculate and monitor trends in the arterial performance measures examined in this study using the considerations developed in this study for a sample set of corridor segments. This approach will help VDOT gain experience and familiarity with these considerations and identify improvements in data quantity and quality in a timely manner so as to use the measures appropriately.*
3. *VDOT's TED and OD should continue to support periodic evaluations of probe-based speed data and network measures (INRIX, NPMRDS, and other vendor data sets of interest) using ground truth data. These exercises will help VDOT understand when the quality of the data improves to levels sufficient for use of the data in more precise target setting. Although evaluation studies conducted so far (e.g., the I-95 Corridor Coalition Vehicle Probe Project [Young et al., 2015] and VDOT internal studies) indicate higher data quality in rural areas and on roads with low signal density and high AADT, no studies have looked at the cumulative effects of the data quality on the network measures that include all the roads in the area. Potential research avenues include the ongoing evaluations by the I-95 Corridor Coalition; permanent benchmark data collected from some arterials in Virginia; VTRC TA studies; and pooled fund studies with other states.*
4. *VDOT's TED and OD should work with VDOT's Information Technology Division to study and mobilize necessary data storage and computational servers for calculating statewide system performance measures. These resources are necessary in order to calculate performance measures for the entire state in a reasonable time frame and to carry out additional sensitivity analyses.*

Implementation

1. On April 22, 2016, the Federal Highway Administration posted an NPRM in the *Federal Register* (2016) to propose national performance management measure regulations to assess the performance of the National Highway System. The comment period ended August 20, 2016. VTRC staff used the findings of this study to support the effort of VDOT's TED and OD to comment promptly and appropriately on this proposed rulemaking as part of the TA project titled "VDOT Travel Time Research Program."
2. As part of the TA project, in FY17 and FY18, VTRC will develop tools, a schedule, and a format for calculating performance measures and monitoring trends in the measures and the data quality. VTRC will share the tools and results from that project with VDOT's TED and OD and set up an ongoing monitoring program in cooperation with the TED and OD. That

effort will include roadways with diverse characteristics, including rural, urban, and suburban routes.

3. The TA project is already scoped for VTRC to carry out limited data validation and performance measure assessments. The I-95 Corridor Coalition Vehicle Probe Project studies (Young et al., 2015) also carry out data validation studies across various corridors in the member states. Both of these projects have been set up on a continuing schedule to perform spot studies as needed.
4. VDOT's TED and OD will work with VDOT's Information Technology Division to identify data storage and computational server needs and study big data approaches to resolving those needs. These tasks will be carried out in FY17 and FY18 in time to calculate and report system performance measures to the U.S. Department of Transportation for MAP-21 compliance.

FINAL REPORT

**CONSIDERATIONS FOR CALCULATING ARTERIAL SYSTEM
PERFORMANCE MEASURES IN VIRGINIA**

Ramkumar Venkatanarayana, Ph.D.
Research Scientist

INTRODUCTION

The Moving Ahead for Progress in the 21st Century Act (MAP-21) is the federal transportation legislation signed into law in July 2012. MAP-21 stated that “the Secretary [of the U.S. Department of Transportation] . . . shall promulgate a rulemaking that establishes performance measures and standards.” Further, the act stated: “Not later than 4 years after the date of enactment of the MAP-21 and biennially thereafter, a State shall submit to the Secretary a report that describes (1) the condition and performance of the National Highway System in the State; . . . [and] (3) progress in achieving the performance targets identified.”

On April 22, 2016, the Federal Highway Administration (FHWA) posted a Notice of Proposed Rulemaking (NPRM) in the *Federal Register* (2016) to propose national performance management measure regulations to assess the performance of the National Highway System (NHS). The period for comments ended August 20, 2016.

To provide appropriate comments on the NPRM, and for federal compliance thereafter, the Virginia Department of Transportation (VDOT) Traffic Engineering Division (TED) and Operations Division (OD) championed this study in 2013. The VDOT Business Plan for Fiscal Year 16 (FY16) (VDOT, 2015) also supported this approach through Action Item 5.6.1 (i.e., respond to notices of proposed rulemakings within designated time frames and coordinate cross-functional working teams) and the goal with regard to performance management (i.e., incorporate requirements of MAP-21 into VDOT’s performance management program). This study assessed current data availability; identified potential system performance measures; calculated the performance measures for a study network using different calculation factors; analyzed the results for different geometric and traffic factors; and developed a number of recommendations.

PURPOSE AND SCOPE

The purpose of this study was to support VDOT’s efforts to comply with MAP-21 arterial system performance measurement and reporting mandates and assist VDOT in making more informed operations and resource allocation decisions. The word “arterial” is used in this report to mean any surface street that is not access controlled. This includes both signalized and unsignalized facilities.

The objectives of this study were as follows:

- *Identify candidate performance measures based on a review of current arterial congestion and system reliability performance measures used by other states and in previous studies.*
- *Identify data needs to support VDOT's performance measurement and reporting, and inventory current VDOT data to identify additional data needs.*
- *Develop guidance for weighting performance measures to calculate the aggregate measures at the corridor/network/urban area/district/region/state levels from data at the link/segment levels.*
- *Develop recommendations for logically defining roadway segments for calculating and monitoring performance measures for internal VDOT applications.*
- *Study the effect of missing data (less than ideal data quality) on the candidate performance measures.*
- *Study the effect of the definition of "truck" in terms of vehicle classes on freight measures.*

The scope of this study was limited to congestion and system performance measures of arterial networks. This study used a sample network from the Hampton Roads area, not the entire state. For interstates and NHS-other freeways in Virginia, VDOT recently consulted with the Texas A&M Transportation Institute to generate congestion and reliability measures.

The Mobility Measurement in Urban Transportation Pooled Fund Study is also currently carrying out a synthesis project on arterial system performance measurement that addresses thresholds and target setting. The results from that study are expected to be practice-ready for VDOT, and hence these two topics were not included in the main scope of this study.

METHODS

Four main tasks were undertaken to achieve the study objectives:

1. A literature survey was conducted to identify potential performance measures for use in arterial performance monitoring, calculation methodologies, factors influencing the measures (such as threshold speeds for defining delay), spatial segmentation, data requirements and sources, and visualization approaches effective for communicating the performance measures. Then, performance measures considered appropriate for Virginia were selected in coordination with the project's technical review panel (TRP) and were carried through the remaining tasks.

2. For the performance measures selected in Task 1, the data required to calculate each measure were identified and available data in Virginia were inventoried. Gaps in data were identified.
3. The selected performance measures were calculated for a sample network (i.e., the study network) and analyzed with respect to data source and calculation methodologies. The study network was defined in cooperation with the TRP. In the selection of the routes for the study network, diverse characteristics were considered that would allow results to be applicable to the rest of Virginia.
4. Based on the results of the analyses performed in Task 3, recommendations were developed for calculating appropriate Virginia arterial performance measures.

Task 1: Conduct Literature Review and Select Performance Measures for Study

The literature on arterial system performance measures and their calculation methodologies was identified primarily through the TRID database and FHWA's Office of Transportation Performance Management (FHWA, n.d.). The literature included journal articles, state transportation agency reports, and established manuals. The literature was reviewed to identify measures, calculation methodologies, and factors of interest to this study, including threshold speeds for defining delays, spatial segmentation, and weighting. The review also identified data needed to calculate performance measures and visualization approaches for communicating the measures. Then, performance measures for this study were selected with input from the TRP.

Task 2: Identify Data Needed to Calculate the Selected Performance Measures and Inventory Their Current Availability in Virginia

The data needed and currently available in Virginia to calculate the selected performance measures were identified and documented. The focus of this task was the availability of data for performance measurement and reporting purposes and not real-time traveler information or operations. Data gaps were also identified.

Task 3: Calculate the Selected Performance Measures for a Sample Network and Analyze Them

Task 3 was broken into three subtasks.

1. Define the study network.
2. Calculate the selected performance measures.
3. Analyze the performance measures with respect to data source and calculation methodologies.

Task 4: Develop Recommendations for Calculating Performance Measures

Based on the results of the analyses performed in Task 3, recommendations were developed for VODT with regard to calculating performance measures and commenting on the NPRM.

RESULTS AND DISCUSSION

Task 1 Results: Literature Review and Performance Measures Selected for Study

Literature Review

Findings from the literature were categorized into major topics and are presented here.

Overview of Performance Measures

Table 1 provides an overview of reviewed arterial system performance measures. In summary, the most frequently reported measures were annual delay and travel time index (TTI) for system congestion and planning time index (PTI) and buffer index (BI) for travel time reliability.

For congestion measurement, three key aspects were emphasized in the literature: extent (as geographic area or number of people affected); duration (in time); and intensity/severity (magnitude of problem or degree of congestion experienced) (U.S. Department of Transportation [U.S. DOT], 2014). In addition, Cambridge Systematics, Inc., et al. (2013) mentioned that “reliability is a feature or attribute of congestion, not a distinct phenomenon.” Thus congestion can be thought of as having these four aspects: extent, duration, intensity, and reliability. Of the literature reviewed, only the Washington State Department of Transportation’s (WSDOT) *Gray Notebook* (WSDOT, 2014) had a measure regarding the extent of congestion. All other literature reviewed focused on the duration and intensity of congestion and reliability, although Eisele et al. (2014) mentioned delay as a measure of extent of congestion. The measure “percentage of congested road-miles” was also mentioned by Pu (2013).

VDOT’s *Traffic Operations Analysis Tool Guidebook* (VDOT, 2013) was developed to help project managers select appropriate traffic analysis tools. The guidebook evaluated many measures and recommended eight of them. The measures of effectiveness (MOEs) recommended for arterial system include queue length, delay, volume/capacity ratio, and speed (average travel speed is combined with speed measure here). Level of service is also mentioned as an illustrator of differences in the MOEs. Of these, although delay can be aggregated up to an entire network, the other three measures do not lend themselves to network-wide aggregation. The guidebook (VDOT, 2013) quotes the *Highway Capacity Manual* (HCM 2010) that “neither LOS [level of service] nor any other single MOE tells the full story of roadway performance, which is why the HCM 2010 provides methods for estimating a variety of useful MOEs.”

Table 1. Overview of Literature Review on Performance Measures

Reference	Performance Measures	Comments
<i>Highway Capacity Manual</i> (HCM 2010) (Transportation Research Board, 2010)	LOS (based on speed and volume/capacity ratio), travel speed, stop rate, automobile traveler perception score, through control delay, through stopped vehicles, 2nd and 3rd term back-of-queue size, capacity	Urban street segments, urban street facilities (composed of multiple contiguous segments), 2-lane highways and multi-lane highways are addressed in 4 separate chapters. Signalized intersections are addressed separately in another chapter. Potentially adverse interactions among modes (autos, bicycles, pedestrians, transit) are explicitly acknowledged. Since probe vehicle data are not limited to through vehicles, when data for through and turning movements are combined, use of HCM methodology may not be appropriate. HCM 2010 does not present area-wide or network-wide performance measures. Turner and Qu (2013) conducted a detailed review of HCM arterial system performance measures (see Appendix A). HCM documents concepts and does not use a specific data source.
<i>Developing Twin Cities Arterial Mobility Performance Measures Using GPS Speed Data</i> (MnDOT Report) (Turner and Qu, 2013)	Annual hours of delay per mile, hours of target delay per mile, TTI, PTI, top N congested segments	This is the only detailed performance report in the reviewed literature that focused extensively on arterial system congestion and reliability calculated using commercially available GPS data. For calculating delays, daytime light traffic speed (average of the two highest hourly speeds during the 14 daytime hours from 6 AM to 8 PM) is used. Authors used INRIX average (by hour and day of week) speed data, state traffic volume data, and roadway geometry (for conflation and intersection density).
AASHTO SCOPM Report (AASHTO, 2012)	Annual hours of delay, reliability index (RI80)	Input was obtained from state DOTs to develop consensus and recommend MAP-21 measures to U.S. DOT. The same 2 measures are recommended for general traffic analysis and freight analysis. RI80 is similar to PTI with 80th percentile travel time. More calculation details are presented in Appendix A. The report documents concepts and does not use a specific data source.
<i>2012 Indiana Mobility Report</i> (Remias et al., 2013) and <i>2013-2014 Indiana Mobility Report</i> (Day et al., 2014)	Congestion hours, distance-weighted congestion hours, congestion index, speed profile, speed deficit, travel time deficit, congestion cost, top N bottlenecks	The 2012 report focused on freeway performance. Some arterial performance is reported. The report does not describe how corridor travel times were calculated from segment travel times or what segment lengths were used and why (based on note that smaller segments are now used in calculations, it is inferred that INRIX Traffic Message Channels were used directly). Congestion hours summed all time intervals across all segments when average 15-min speed fell below a threshold (45 mph). The report used commercial third-party vendor data based on GPS devices and other probes.
<i>2013 Maryland State Highway Mobility Report</i> (Mahapatra et al., 2013)	Number of intersections in 3 LOS categories (D or better, E, F), miles of roadway in each direction in the 3 categories, list of intersections and road segments at LOS E and F, top N bottlenecks for freeways	The report focused on freeway measures. For arterials, focus was individual route HCM measures of LOS. No statewide or region-wide arterial performance measures were reported. Additional information was included for each corridor as background: corridor length, functional class, speed limit, number of travel lanes in each direction, number of signals, number of grade-separated interchanges, major cross streets, average daily traffic, % trucks, and design hourly volume. The report used procedures similar to RITIS VPP Suite in effect then. Bottlenecks are said to occur when speeds drop below 60% of free flow speed for longer than 4 min. Impact factor is multiplication of total annual number of bottleneck occurrences by their average duration and by their average length. Bottlenecks and freeway measures used INRIX speed data. Arterial measures used intersection-level data (mode of data collection not reported).
MoDOT Tracker (MoDOT, 2013)	Average travel time per 10 miles, additional travel time needed for on-time arrival 80% of time, annual congestion costs	System congestion and reliability are small portions of the report. Measures are reported only for the 2 metro areas. Using roadside sensors and driving the routes (at least 2 times in AM and PM peak hours) are the main data collection methods. AM and PM rush hours are not defined. Mobility map displays high (green), medium (yellow), and low (red) levels. The report mentions use of RITIS and travel time data using wireless technology.
<i>Urban Congestion Report</i> (UCR) (FHWA, 2015b)	Congested hours, TTI, PTI	The report focuses on freeways and does not include arterial streets. UCR uses HPMS volume data and 15-min aggregated NPMRDS data by day of week and month.
RITIS VPP Suite (UMD CATT Lab, n.d.)	TTI, BI, and PTI (95th percentile); user delays; user delay costs; bottlenecks	The RITIS VPP Suite calculates the performance measures for user-selected corridors or regions. Although the suite documentation provides same definitions and calculation methodology as UCR, personal communication with the RITIS team revealed variations. BI and PTI use the 95th percentile 1-min speed values for all days and time range selected. BI uses historic average speed provided by INRIX. Free flow speed is reference speed provided by INRIX. Average speed for TTI is average of observed speeds for

Reference	Performance Measures	Comments
		selected days and time period. RITIS VPP Suite hosts HERE, INRIX, and TomTom data in addition to NPMRDS. Average traffic volumes from Virginia roads are part of the system.
WSDOT <i>Gray Notebook</i> (WSDOT, 2014) and <i>Corridor Capacity Summary</i> (WSDOT, 2013)	Lane-miles (and % of system) congested, per person, total and cost of delay, TTI for select corridors	<i>Congestion</i> is defined as speeds below 70% of the posted speed limit. Delays are based on maximum throughput speeds (85% of posted speed limit). Vehicle miles traveled and miles traveled per person are also reported. TTI is calculated with the reference speed where throughput is maximum (rather than free flow speed) and is called MT3I (Maximum Throughput TTI). MT3I is calculated for 52 corridors in Puget Sound area (which has 97.5% of statewide delay). Daily congested segments are identified on individual corridors with segment length and hours. Congested miles are calculated from annual average speed profiles. Each Traffic Message Channel that is congested for 1 or more hours is considered in the congested miles summation. Corridor measures included annual miles traveled per person, annual delay per person, annual emissions per person, SOV-HOV travel times (average and 95th percentile), peak period transit ridership (and % seats occupied), highway productivity as percentage (based on highest observed 5-min flow rate), transit capacity, park and ride capacity, prominent bottlenecks, additional travel time (buffer) from previous year average, trip reliability (in minutes), congestion and gas cost per person, and average peak period travel times. The reports use speed and volume data from loop detectors, automated license plate readers, Bluetooth, Wavetronix, vehicle detection, and private sector speed data.
2012 <i>Urban Mobility Report</i> (UMR) (Schrang et al., 2012) (UMR renamed <i>Urban Mobility Scorecard</i> in 2015)	Travel speed, travel delay, annual person delay, annual delay per auto commuter, total peak period travel time, TTI, CSI, PTI, RCI, number of rush hours, percent of daily and peak travel in congested conditions; percent of congested travel	The report focused on urban areas and included freeways and arterials. Daily VMT was estimated from HPMS and local transportation data sources. Population data were obtained from the U.S. Census Bureau and HPMS. Peak period travelers are estimated from the National Household Travel Survey. Total peak period travel time is ratio of total VMT in peak to average speed (multiplied by a constant 1.25 persons per vehicle). CSI is same as TTI except that it includes only travel in peak direction. PTI is presented only for freeways. Daily average delays are calculated for all 7 days of the week, and their sum is multiplied by 52 to get annualized delays. RCI combines freeway and arterial VMTs and lane miles to derive an index that is not sensitive to operational changes. Number of rush hours is based on area-wide TTI value and population. The last 2 measures are calculated from estimated speeds, rather than probe speed data. The report uses INRIX speed data and HPMS volume data.
VDOT Pilot Study: <i>2010 Traffic Performance Measures Development Using INRIX Travel Time Data</i> (JMT Technology Group and Vanasse Hangen Brustlin, Inc., 2012)	Delay per vehicle, total delay, TTI, BI, PTI, percent on-time arrival, congested travel, percent of congested travel, misery index	This was a recent work in Virginia, overseen by VDOT's Traffic Engineering Division. Three freeway routes and 2 arterial routes were studied. Both types of roadways were treated similarly for performance measure calculations. Holidays were excluded from the calculations. Measures were calculated only for 250 workdays. % on-time arrival is calculated as % of days when peak period travel time is less than 1.1 times mean peak period travel time. "Congested travel" is defined as the product of corridor length and peak period volume (resulting in VMT). % of congested travel is calculated for each corridor and peak period for workdays as ratio of average peak period delay to average peak period travel time multiplied by hundred. Misery index is defined as $[\text{Mean}(\text{Top } 20\% \text{ travel time})/\text{Mean travel time} - 1]$. The report used INRIX speed data.
FDOT <i>Performance Report</i> (FDOT, 2013b) and <i>Mobility Performance Measures Program Consensus Items</i> (FDOT, 2013b)	Highway travel time reliability, vehicle hours of delay, percent miles severely congested, VMT. Mobility performance measures grouped into quantity, quality, accessibility, and utilization.	Travel time reliability is % of travel greater than 45 mph on freeways. Percent miles severely congested is % of roadway miles operating at LOS F in peak hour. Quantity includes VMT and person miles traveled. Quality includes % travel and % miles meeting LOS criteria, travel time reliability and variability, vehicle and person hours of delay, and average travel speed. Accessibility measures % population within 30 min of job. Utilization includes hours, % miles, and % travel severely congested and vehicles per lane mile. Data source is not documented.
<i>INRIX Traffic Scorecard</i> (INRIX, 2015)	INRIX TTI, wasted time in congestion	INRIX TTI is defined as % increase in average travel time of a commute above free flow conditions. TTI is calculated hourly over a single week. Wasted time in congestion is calculated as monthly and annual delay totals,

Reference	Performance Measures	Comments
		using average delay from a typical commute trip, typical commute trip length and number of trips typical commuter takes in a month or year. A 30-min trip time is used in U.S. INRIX speed data are used.
<i>TomTom Traffic Index</i> (TomTom, 2016)	Congestion level percentage	Extra travel time a driver will experience compared to an uncongested situation. The report uses TomTom speed data.

LOS = level of service; MnDOT = Minnesota Department of Transportation; TTI = travel time index; PTI = planning time index; AASHTO = American Society of State Highway and Transportation Officials; SCOPM = AASHTO Standing Committee on Performance Measurement; DOT = department of transportation; RITIS = Regional Integrated Transportation Information System; RITIS VPP Suite = RITIS Vehicle Probe Project Suite; MoDOT = Missouri Department of Transportation; GPS = global positioning system; NPMRDS = National Performance Management Research Dataset; HPMS = Highway Performance Monitoring System; BI = buffer index; WSDOT = Washington State Department of Transportation; VMT = vehicle miles traveled; SOV = single occupancy vehicle; HOV = high occupancy vehicle; CSI = commuter stress index, RCI = roadway congestion index; FDOT = Florida Department of Transportation.

According to Eisele et al. (2014), recent research has noted a specific downside of BI: when average travel times decrease more than the 95th percentile travel time, BI will increase, even though both average congestion and reliability have improved. Therefore, the authors recommended PTI over BI for a reliability measure. Juster et al. (2015) calculated these indices using median and 15th percentile travel times, instead of average and free flow travel times. In the *Urban Congestion Report* (UCR), holidays are not used as valid weekdays in the calculations (FHWA, 2015b). All federal holidays and one extra day around Thanksgiving and Christmas are excluded from calculations. Further, specific dates, times, and road sections that have failed a visual quality control check are separately listed as “bad days” and excluded from calculations on a section-by-section basis.

In a report on travel time reliability by the Texas Transportation Institute and Cambridge Systematics, Inc. (2006), the authors stated that “discretion should be used when directly comparing travel times from different methods, as each method may have unique but consistent internal biases.” Understanding these biases and internal consistencies is especially important for communicating and using performance measures for decision making at different levels of aggregation. For state- or regional-level measures, vast representative spatial coverage is likely more important than perfect data accuracy. However, for corridor- or intersection-level measures, detailed and accurate data are likely needed, even if they cover only a short time interval. The resources of money, personnel, time, and equipment required for these two different types of data collection and analyses are vastly different, and the measures estimated thereby may not be consistent.

Freight-Specific Measures

According to MAP-21, “the [U.S. DOT] Secretary shall establish measures for States to use to assess freight movement on the Interstate System.” However, the subsequent Fixing America’s Surface Transportation Act (FAST Act) repealed the Primary Freight Network and National Freight Network from MAP-21 and directed the FHWA Administrator to establish a National Highway Freight Network (NHFN) to direct federal resources and policies strategically toward improved performance of highway portions of the U.S. freight transportation system (FHWA, 2016a). According to the FAST Act National Highway Freight Program (FHWA, 2016b), the U.S. DOT Secretary is in the process of promulgating a rulemaking that will provide guidance on freight performance measurement, establishment of targets, determination of

whether a state is making significant progress to meet targets, etc. In addition to the NHFN defined by the U.S. DOT, which mainly includes interstates, states are required to identify critical urban freight corridors and critical rural freight corridors. In Virginia, the NHFN includes three arterial segments: the International Terminal Boulevard, VA 337, and VA 168. The last two segments are part of the study network in this study.

The literature search did not identify many studies or reports addressing system performance measures for trucks or freight, especially related to travel reliability on the arterials. However, observations from relevant reviewed literature are presented here.

Gordon Proctor & Associates et al. (2011) provided these valuable insights:

- Freight performance measure use is low.
- States use only a handful of freight measures and include generic measures such as travel time in freight-significant corridors.
- Most of the (freight) measures appear to be indicators of broad trends of overall transportation system performance.
- An AASHTO task force on examining freight performance measures recommended three measures: travel speeds on the freight-significant routes, reliability on freight-significant routes, and border crossing delay.

Specific freight measures mentioned included the following:

- Speeds, travel times in freight-significant corridors, delays, travel rate (time taken to travel a distance of 1 mile), percentage of segments in each corridor where average speeds were less than 50 mph, miles of congested roadway, miles of congested travel.
- Reliability measures:
 - Statistical range: travel time window, percent variation, variability index
 - Buffer measures (considered as “time allowance”): buffer time, BI, and PTI
 - Tardy trip indicators (considered as “the unreliability impacts using the amount of late trips”): Florida reliability method (which measures travel time during the peak), on-time arrival measures, and misery index (which measures the most congested 20% of travel periods).
- Truck volumes, traffic volumes, and volume/capacity ratios.
- Significant truck freight bottlenecks based on a congestion index, which is the sum of the 24 hourly freight congestion values: The congestion value for each hour of an average day is calculated by multiplying the truck volume with the difference

between the free flow speed (FFS) and the average speed if speed is below free flow (defined as 55 mph) (Short et al., 2009). Using this methodology, Keenan et al. (2012) presented the top 25 freight bottlenecks in the United States.

- Freight tonnage.

In its report, the AASHTO SCOPM (AASHTO, 2012) proposed only one measure for freight: annual hours of truck delay. This measure is similar to the annual hours of delay measure proposed for all traffic and uses truck volumes instead of the all traffic volume. Further, this measure was proposed only for the interstate highway system.

According to Rhodes et al. (2012), efficient urban freight movement depends on a number of diverse measures besides congestion. The authors focused on local decisions that influence urban freight movement performance and covered several topics including zoning regulations, local ordinances, parking and loading, and route or time restrictions. The authors also examined 12 specific urban supply chain cases in detail. Of note to the current study, congestion and/or delay was repeatedly mentioned as a risk to performance for most supply chain cases studied.

Mallett et al. (2006) presented two freight truck congestion performance measures: average speed and 95th percentile BI. Freight-significant corridors were determined using AADT and AADTT values. Congestion and delay were mentioned as serious problems also during weekends—especially in major metropolitan areas, in recreational tourist areas, and during special events.

In the 2012 *Urban Mobility Report* (UMR), Schrank et al. (2012) presented truck commodity value in the urban areas studied. The authors' methodology was based on the Freight Analysis Framework and the Highway Performance Monitoring System (HPMS) and may provide a useful context for studying system congestion or reliability.

The 2010 *Virginia Statewide Multimodal Freight Study* (Cambridge Systematics, Inc., et al., 2010) used AADT, AADTT/AADT, and number of lanes to determine road performance and did not use any speed data. The freight bottlenecks in Virginia were identified only qualitatively.

Belfield and Nichols (2012) defined trucks as vehicle classes 5 through 13. In addition to this definition, the technical review panel for the current study was interested in the effect of defining trucks as vehicle classes 6 through 13.

Threshold Speeds

For calculating delays from travel time or speed data, a threshold speed is necessary. This threshold speed is also sometimes referred as the reference speed. Eisele et al. (2014) described this threshold as “when to start ‘counting’ delay.” VDOT may have to determine the threshold if the published final rule follows the recommendation in the AASHTO SCOPM report (AASHTO, 2012) to allow flexibility to the states with regard to this threshold.

The reviewed literature contained several methods for determining threshold speeds, mostly focused on freeways:

- Remias et al. (2013) used 45 mph for freeway congestion measurement.
- Eisele et al. (2014) mentioned that a common approach to estimate FFS is to use the 85th percentile speed in the off-peak period, which may effectively capture the essence of the definition in HCM 2010 (Transportation Research Board [TRB], 2010).
- The Texas A&M Transportation Institute, in its 2013 freeway performance measurement report for VDOT (unpublished data), recommended using FFS, defined as the INRIX reference speed.
- The Missouri Department of Transportation (MoDOT) Tracker (MoDOT, 2013) mentioned that the posted speed limit (PSL) is the desired outcome for travel conditions.
- Short et al. (2009) used 55 mph as the FFS to measure freight congestion and hence bottlenecks.
- Gordon Proctor & Associates et al. (2011) used 50 mph for measuring freight congestion.
- The AASHTO SCOPM report (AASHTO, 2012) mentioned different methods to determine thresholds (35 mph used in California to identify serious congestion problems; rural areas may use speed limits or FFSs). The report further listed the following defensible factors in setting location-specific threshold speeds:
 - corridor characteristics
 - local conditions, operational factors
 - community opinion about the desirability of additional capacity in a corridor, existing capacity
 - population growth
 - rural/urban routes
 - level of existing revenues
 - potential investment required to achieve performance levels.
- WSDOT (2013) used different thresholds for different reasons (Table 2). A number of challenges exist with the maximum throughput speed. First, identifying the

maximum throughput speeds under different conditions, such as inclement weather or work zones, is currently not an established practice. Second, the maximum throughputs on signalized arterials are much more difficult to establish than on freeways, owing to local accesses, metering by signals, varying pedestrian flows, etc.

Table 2. Different Speed Thresholds Used by the Washington Department of Transportation

Performance Measure	Speed Threshold	Description
Posted speed	60 mph	Vehicles are moving through a highway segment at the posted speed, but to travel safely at higher speeds and allow sufficient stopping distance, drivers must maintain more space between vehicles. Fewer vehicles can pass through the segment in a given amount of time, and the segment is not operating at maximum efficiency.
Percent of state highway system delayed	85% of posted speeds	Percent of total state highway lane-miles that drop below 85% of the posted speed limit.
Duration of congested period (urban commute routes)	75% of posted speeds (i.e., 45 mph)	The average weekday peak time period (in minutes) when average vehicle speeds drop below 75% of posted speeds (about 45 mph). Drivers have less than optimal spacing between cars, and the number of vehicles that can move through a highway segment is reduced. The highway begins to operate less efficiently under these conditions than at maximum throughput.
Percent of state highway system congested	70% of posted speeds	Percent of total state highway lane-miles that drop below 70% of the posted speed limit.
Severe congestion	60% of posted speed (i.e., 36 mph)	Speeds and spacing between vehicles continue to decline on a highway segment, and highway efficiency operates well below maximum productivity.
Maximum throughput speed (optimal flow speed)	70%-85% of posted speed (about 42-51 mph)	Vehicles are moving slower than the posted speed, and the number of vehicles moving through the highway segment is higher. These speed conditions enable the segment to reach its maximum productivity in terms of vehicle volume and throughput (based on the speed/volume curve). This threshold is used for highway system deficiency analysis.

Compiled from Washington State Department of Transportation. *2013 Corridor Capacity Summary*. Olympia, 2013.

Threshold speed calculation methods for arterials in the reviewed literature were as follows:

- Turner and Qu (2013) used two thresholds for arterials: target speed (defined by the agency), and light traffic speed (LTS) (defined as the average of the fastest 2 hourly speeds during the daytime 14 hours from 6 AM to 8 PM). One concern with the latter threshold is that for each segment, 1 or 2 hours of daytime will be deemed to have no delay, which is questionable in dense metropolitan areas.
- The 2012 UMR (Schrank et al., 2012) used the average speed during low volume conditions (10 PM-5 AM). The freeway threshold speeds were capped at 65 mph. Arterial speeds were not capped. The authors mentioned that there has been considerable debate about the appropriate congestion thresholds.

- The Regional Integrated Transportation Information System (RITIS) Vehicle Probe Project (VPP) Suite (RITIS VPP Suite) (UMD CATT Lab, n.d.) used the reference speed provided by INRIX. This reference speed is the 85th percentile of observed speed from all time periods, with an upper limit of 65 mph. The same methodology is used for freeways and arterials.
- JMT Technology Group and Vanasse Hangen Brustlin, Inc. (JMT and VHB) (2012) defined route FFS as the 85th percentile speed of the 85th percentile speeds from each Traffic Message Channel (TMC).
- The HCM 2010 (TRB, 2010) used the Base FFS, defined as the FFS on longer segments. It is estimated by using either the observed mid-segment FFSs and a correction factor for segment length or PSL and factors for median restriction, curb presence, and access point density from previous empirical research findings.
- In an unpublished report under the Mobility Measurement in Urban Transportation Pooled Fund Study (dated May 27, 2013), the advantages and disadvantages of using the HCM 2010 (TRB, 2010) Base FFS and calculating the LTS from the two fastest speeds during daytime are described (Table 3) (M. Fontaine, personal communication). The report cited Turner and Qu (2013) for the latter approach.

It should be noted that the different threshold speeds result in relative differences in delay and other performance measures at comparable segments but practically do not impact ranking or performance trend monitoring. However, when delays and other measures are compared across dissimilar segments or aggregated to calculate network measures, the final impacts attributable to threshold speed definitions are difficult to understand. For example, a lightly congested rural segment and a heavily congested urban segment may have a similar TTI when daytime LTS is used as the threshold speed.

Table 3. Comparison of Highway Capacity Manual and Texas A&M Transportation Institute Methods for Defining Free Flow Speeds

Position	HCM Free Flow Speed That Does Not Include Routine Signal Delay	Texas A&M Transportation Institute Free Flow Speed That Includes Routine Signal Delay
Pros	<ul style="list-style-type: none"> • FFS measures total delay because of the traffic signal system (i.e., delay occurs in an optimized signal system). • Consistent HCM approach since 1985. • FFS can possibly be obtained from mid-block GPS probes in commercial speed data. 	<ul style="list-style-type: none"> • FFS can be directly calculated from commercial speed data. • FFS as a “target” can be reached (without removing all signals).
Cons	<ul style="list-style-type: none"> • FFS as a “target” can never be met (unless signals are removed), even in an optimized signal system. • Current estimation procedure requires data not readily available in state DOT or city roadway inventories. 	<ul style="list-style-type: none"> • Does not capture delay that occurs in light traffic because of suboptimal signal timing. • Even if FFS as a “target” is met, there may still be improvements possible (e.g., suboptimal timing in light traffic). • FFS in light traffic can be different for different times of the day (when time-of-day signal operation is used).

Source: Turner, S., and Qu, T. Developing *Twin Cities Arterial Mobility Performance Measures Using GPS Speed Data*. Minnesota Department of Transportation, St. Paul, 2013.

HCM = *Highway Capacity Manual*; FFS = free flow speed; GPS = global positioning system; DOT = department of transportation.

In summary, the transportation community currently has no broad consensus on the topic of threshold speeds. Further, Remias et al. (2013) mentioned that threshold speed determination for the arterial systems poses a unique challenge because of the control devices. On arterials, motorists often travel below the speed limit or FFS and experience congestion owing to signals, stops, and accesses. These inherent delays in a signal system are explicitly recognized in the 2009 *Manual on Uniform Traffic Control Devices* (FHWA, 2009). VDOT may therefore find it easier to communicate with the public and elected officials by using the FFS or PSL as the threshold to define delay. VDOT may then define different “targets” for different corridors or regions as acceptable delays based on available resources, community vision, etc.

Segmentation

Different segmentation lengths and approaches were used or recommended in the reviewed literature (Table 4).

Table 4. Segment Lengths in Reviewed Literature

Segment Length	Study/Reference
1 mile	<i>Using Truck GPS Data for Freight Performance Analysis in the Twin Cities Metro Area</i> (MnDOT) (Liao, 2013)
3 miles and 50 miles	<i>Performance Measures for Freight Transportation</i> (Gordon Proctor & Associates et al., 2011); <i>Freight Performance Measurement: Travel Time in Freight-Significant Corridors</i> (Mallett et al., 2006)
5 miles and 10 miles	Cambridge Systematics, Inc., and Texas A&M Transportation Institute (2005) (for incident delay analyses)
10 miles	Cambridge Systematics, Inc., and Texas A&M Transportation Institute (2005) (for freight performance)
TMC lengths	<i>2012 Urban Mobility Report</i> (Schrang et al., 2012), RITIS VPP Suite (UMD CATT Lab, n.d.), <i>2012 Indiana Mobility Report</i> (Remias et al., 2013)
Different lengths, based on speed data	<i>Auto-Segmentation Method for MAP-21 Performance Measure Reporting Using Large Statewide Speed Datasets</i> (Wikander et al., 2014)
Entire route as one segment	<i>2010 Traffic Performance Measures Development Using INRIX Travel Time Data</i> (JMT Technology Group and Vanasse Hangen Brustlin, Inc., 2012)
Defined by the state DOTs and MPOs	AASHTO SCOPM report (AASHTO, 2012)
Not too long or too short	<i>Standardized Data Processing: When Is It Needed in the Mining of Private-Sector Probe-Based Traffic Data to Measure Highway Performance?</i> (Pu, 2013); <i>2010 Traffic Performance Measures Development Using INRIX Travel Time Data</i> (JMT Technology Group and Vanasse Hangen Brustlin, Inc., 2012)
Different lengths, based on road geometry and AADT/traffic characteristics	<i>Developing Twin Cities Arterial Mobility Performance Measures Using GPS Speed Data</i> (MnDOT) (Turner and Qu, 2013)

MnDOT = Minnesota Department of Transportation; TMC = Traffic Message Channel; DOT = department of transportation; MPO = metropolitan planning organization; AADT = average annual daily traffic.

Predetermined segment lengths (such as 1 or 3 miles) cannot be applied directly to TMC-based probe data, given the TMCs can be of arbitrary lengths. To use predetermined segment lengths with TMC data, some assumptions must be made in reconciling how the segment speed will be calculated from the constituent TMCs. The freight studies that used these predetermined

segment lengths obtained actual GPS tracks from the vehicles, and the authors did their own aggregation to whatever spatial segments they deemed appropriate. Although notable studies and systems used TMC lengths as the base spatial segments, a preliminary examination by the researcher of TMC lengths in Virginia indicated that these lengths can vary from 1/100th of a mile to several miles. Using speed data itself to segment a network may result in different segments over different years, whereby segment-level performance trend monitoring from one year to the next is not possible. JMT Technology Group and VHB (2012) considered an entire route as one segment. The length of these routes ranged from 11 to 60 miles. This method is likely to wash out intense congestion on specific segments of the route and does not meet the authors' own recommendation that "segments [should] not be too long." The approach by Turner and Qu (2013) to use road geometry and traffic characteristics to do segmentation seems most logical and meaningful, although time-consuming initially.

Although segmentation for system congestion monitoring is relatively new, some information is available from established traffic volume monitoring practices. The FHWA's *Traffic Monitoring Guide* (TMG) (FHWA, 2013b) noted:

The character of the road systems and the volumes carried has a major impact in the definition of segments. For roads where access is controlled (such as the interstate system), a simple definition of segments between interchanges is appropriate. For lower systems, clear traffic volume breaks are not always apparent and other rules of thumb (such as major intersections) should be applied. Rural and urban characteristics also require different handling. For the lowest volume roads, the 10 percent rule of thumb may be too narrow and a wider definition is sought. Careful definition of roadway segments can significantly reduce the number of counts needed to cover all highways within an agency's jurisdiction, while still providing the accurate volume data required for planning and engineering purposes.

The "10 percent rule of thumb" is that if two adjacent sections of a roadway differ in AADT by 10% or more, they need to be considered as different segments. The underlying principles used by Turner and Qu (2013) and the TMG are comparable and were used in this study.

Weighting

Weighting methods for different measures in the reviewed literature included the following:

- *Simple average (no weights)*: UCR (FHWA, 2015b) for segment TTI over days of the week since the vehicle miles traveled (VMTs) for different days are similar.
- *Length*: HCM 2010 (TRB, 2010) for facility spatial stop rate—essentially adding up the number of stops at all segments; Remias et al. (2013) for distance-weighted congested hours; Pu (2013) for TTI and PTI; RITIS VPP Suite (UMD CATT Lab, n.d.) for TTI, BI, and PTI; AASHTO SCOPM report (2012) for the AASHTO reliability index (RI80); JMT Technology Group and VHB (2012) for corridor FFS from TMC speeds.

- *Vehicle volume*: HCM 2010 (TRB, 2010) for approach and intersection delays, from average movement delay—essentially adding up all the delays; Smith et al. (2007) for regional and statewide speed index, which is the reciprocal of TTI.
- *Person volume*: Eisele et al. (2014) mentioned that TTI, PTI, and BI were scalable from a link to a roadway section to an urban area by weighting by person-volume.
- *VMT*: Turner and Qu (2013) for TTI and PTI; 2012 UMR (Schrank et al., 2012) for TTI; UCR (FHWA, 2015b) for congested hours, TTI, and PTI; Gordon Proctor & Associates et al. (2011) for TTI.
- *Person-miles traveled*: 2012 UMR (Schrank et al., 2012) for PTI.
- *Number of readings from each segment*: RITIS VPP Suite (UMD CATT Lab, n.d.) so that segments with consistent data are weighted more heavily than those with poor or inconsistent coverage.

Pu (2013) calculated TTI and PTI (95th percentile) using different segment lengths and reported that the segment lengths could have a major effect on the measures themselves and therefore recommended using the segment length as the weighting factor.

Reliability measures are relatively new to the transportation industry. It is not clear if their aggregation (irrespective of the weighting method used) from individual segments to the corridor, region, or state level is even useful or meaningful for a number of reasons including the following:

- *Unreliability for different roads has different causes*. The U.S. DOT (2014) mentioned seven causes of unreliability. Given different solutions are implemented to mitigate these different causes, combining the various types of unreliability into one number is not useful for making tactical decisions. Further, the 2012 UMR (Schrank et al., 2012) stated: “bad weather is often the cause for the longest travel times, and it is really not fair to measure an agency on these situations they have no impact upon.” Therefore, the region- or state-wide unreliability could be significantly high one year and low another year, just because of variations in weather pattern alone. Any traffic improvements made by the transportation agency through geometric or operational solutions could be lost in this variance. Agencies should be careful not to abort such solutions based on the network unreliability measure trend.
- *The statewide unreliability value is calculated from the 80th percentile (or some other percentile) worst traffic of each segment, even though all the network segments do not have the worst traffic together*. The connectivity or redundancy in the network often helps alleviate the unreliability for any specific segment at a specific time. Therefore, the actual, worst unreliability experienced by the motorists using the network at any given time period might be much lower than the picture painted by the previously mentioned method of aggregation.

- *Depending on which trip purpose is chosen as the focus of determining link or regional reliability, different characteristics of the underlying data (such as selecting appropriate days of the week, time of day, or months) are meaningful.* For example, if a daily commuter trip purpose is chosen, weekdays, all months, and AM/PM peak periods are meaningful data characteristics. For tourist and recreational traffic to the beach, the summer months and specific weekends are more appropriate. Further, although most holidays generate higher than usual traffic demand, specific days in the holidays (such as Thanksgiving Day or the Sunday before Labor Day) often generate lower than usual traffic demand. These details are important for quantifying and managing holiday traffic trends.
- *When speed or volume data quality is low or if data are not available, determining whether the segment for that time period had low or high congestion requires further scrutiny.* For example, during winter weather storms, if a state of emergency is declared resulting in closings of offices and schools, even though some reported traffic speeds may be relatively high owing to low traffic volume demand, the roads are in fact affected highly by the weather event. As such, these data records may best be considered to be indicative of highly unreliable traffic.
- *During full road closures, travel time across the closure is not a meaningful concept.* None of the reviewed literature addressed this singularity in the traffic data from such full road closure situations. In most cases, one should consider these situations abnormal and the corresponding segment unreliable, rather than ignoring the data or assuming free flow travel. Further, during full road closures on one road, even though the neighboring detour routes have high travel unreliability, the cause and hence the unreliability should logically be attributed to the main route.

Aggregating reliability measures for very long corridors, such as the entire length of U.S. 17 in Virginia, or even in the Hampton Roads Metropolitan Planning Organization (MPO), is also subject to many of the challenges listed. However, there is an audience and need for such reliability measures for shorter corridors that motorists traverse regularly. An example is U.S. 17 in York County. Further understanding of these listed factors will evolve as VDOT and localities apply different weighting factors and examine the results over time.

Data Quality

The reviewed literature rarely addressed quality needs for using probe-based speed data to calculate arterial performance measures. Young et al. (2015) performed the most comprehensive evaluation of the arterial speed data. They studied 14 arterial corridors in five states, covering 320 miles, and recommended rules of thumb for arterial data quality adequateness and usability for performance measure calculations, as indicated in Figure 1. Bluetooth data were used as the benchmark.

✓ RECOMMENDED	🔑 SHOULD BE TESTED	✗ NOT RECOMMENDED
<ul style="list-style-type: none"> ● ≤ 1 signal per mile ● AADT > 40,000 vpd (2-way) ● Limited curb cuts <p>Principal Arterials Likely to be accurate...</p>	<ul style="list-style-type: none"> ● 1 to 2 signals per mile ● AADT 20K to 40K vpd (2-way) ● Moderate number of curb cuts <p>Minor Arterials Possibly accurate, test ...</p>	<ul style="list-style-type: none"> ● ≥ 2 signals per mile ● AADT < 20K (2-way) - low volume ● Substantial number of curb cuts <p>Major Collectors Unlikely to be accurate...</p>

Figure 1. Arterial Data Usability Recommendations. From Young, S.E., Hamed, M., Sharifi, E., Juster, R.M., Kaushik, K., and Eshragh, S. *I-95 Corridor Coalition Vehicle Probe Project Validation of Arterial Probe Data: July 2015: Summary Report*. Prepared for I-95 Corridor Coalition. 2015. Reproduced with permission of I-95 Corridor Coalition. AADT = average annual daily traffic.

The four main measures they used to determine data quality were as follows:

1. average absolute speed error (within each 5 mph speed bin)
2. speed error bias (as the average speed error within each bin)
3. slowdown analyses (how often and fully vendor data captured situations when speeds dropped at least 10 to 15 mph for 30 minutes or longer)
4. visual judgment of cumulative frequency distributions (CFDs).

Two other major findings of interest from this study were the following:

1. Probe data consistently overestimated speeds during congestion.
2. Probe data reported the higher of two speed values if the underlying traffic exhibited bimodal distribution of speeds, owing to some vehicles passing through or stopping at red lights.

Cambridge Systematics, Inc., et al. (2013) presented four data quality rules based on their examination of arterial probe data:

1. Any days with extremely low or high travel times should be removed by visual inspection.
2. All travel time for a section should be ranked, and any value greater than the 75th percentile plus 1.5 times the interquartile distance, or less than the 25th percentile minus 1.5 times the interquartile distance, should be treated as an outlier. This technique is robust because it uses the quartile values instead of variance to describe the spread of the data.
3. Two consecutive travel times cannot change more than 40%.

4. A travel time cannot be more than one standard deviation above or below the moving average of the 10 previous entries. These 10 previous entries must be continuous and valid data.

The authors clearly stated that these rules work well for freeway data but that arterial data are considerably more sparse. However, the authors were not clear with regard to some important details. For example, they did not mention the inherent high variabilities in arterial travel times owing to control delays as a challenge in assessing data quality. They did note that order statistics, as in the second test, are considerably difficult to process mathematically. Although the UMR (Schrank et al., 2012) was cited as a reference in the third test, the UMR itself used a different data source (individual toll tag data from Houston [Texas] freeways) and used a threshold of 45%. So it is not clear if and how much the UMR version of the rule would apply for aggregated data on arterials. For the fourth test, the authors did not mention the time interval of aggregation for the data, i.e., whether it should be 1 minute, 10 minutes, etc.

Hallenbeck et al. (2015) recently used NPMRDS freeway data in Washington State to compute performance measures and found delay errors on the magnitude of 4 to 8 times that calculated using loop detector data for a 14-mile corridor for weekdays in October 2014. On the topic of data quality, the authors stated “FHWA is aware that the NPMRDS may be unable to meet the MAP-21 performance monitoring needs for which it was purchased.” They recommended that WSDOT use NPMRDS data for ranking delay locations but not to track trends. They expect the data quality to improve over time, as it has done in the past. Kaushik et al. (2015) analyzed NPMRDS data for arterials and mentioned that the data is both sparse and contains outliers. They mentioned that the outlier detection algorithms applied to Bluetooth data can be used for NPMRDS data.

Rafferty and Hankley (2014) also mentioned missing observations and outliers in NPMRDS data and their effect on the calculated measures. They stated that calculating the 95th percentile travel time from just the available data will likely result in overestimation. They assumed that the missing data were below the 95th percentile and hence counted down from the available records to estimate the 95th percentile travel time. For example, if 200 speed values were available from an expected 300 records, instead of taking the 10th highest value as the 95th percentile travel time, they used the 15th highest value. These authors stated that outliers have a negligible effect on summary statistics and reliability measures but highly affect delay calculations. They recommended, at a minimum, removing observations that are several standard deviations above the mean. They also mentioned that an even better approach is to outlier detection is to compare an observation to its neighboring data.

The Texas A&M Transportation Institute and Cambridge Systematics, Inc. (2006) sounded the following caution on data quality:

ensure that accurate and valid travel times are used in the calculation steps. Quality assurance may be more significant . . . if the travel time data have been collected for real-time applications but archived for historical use (such as with archived probe vehicle or detector data from traffic operations). The real-time applications may have different quality requirements; thus, additional quality assurance may be necessary. Quality assurance for periodic special studies (such as floating car runs) should be integrated throughout the data collection and reduction process.

The authors further stated:

It is recognized that all methods of calculating or estimating travel time data produce some error. Professional judgment should be used to determine whether the likely estimation errors exceed those permissible for the applications of the reliability measures. Agencies should also recognize that near-term and future advances in traffic monitoring are likely to provide more than sufficient quantity and quality of travel time data for reliability measures.

However, no specific data quality checks or reasonability tests were presented for probe-based speed data.

INRIX marks each 1-minute data record with a self-reported confidence score of 10, 20, or 30, explained as follows (INRIX, 2014):

- *30*: real-time data, with no historic fusion
- *20*: historic average speed for that time period for the period 4 AM to 10 PM; sufficient real time information is not available
- *10*: reference speed for the period 10 PM to 4 AM or for any TMC and any time period if historic average speed is not available; sufficient real time information is not available.

RITIS VPP Suite (UMD CATT Lab, n.d.) currently provides an option of selecting specific confidence scores for downloading data, but not for performing analyses such as user delay costs or bottlenecks. Missing values are simply ignored in the calculations. It should be noted that this approach can skew the final results. The TMG (FHWA, 2013b) has a long history of providing detailed guidance for data quality and aggregation of traffic volume data. It recommends the use of representative volume profile data for each hour, each day of the week, and each month for calculating AADTs. The 2012 UMR (Schrank et al., 2012) used a similar approach for averaging speed data, which is applicable for measures such as annual travel delay or TTI. However, reliability measures such as BI and PTI depend on the accurate availability of the relevant (80th or 95th) percentile data. JMT Technology Group and VHB (2012) did not mention data quality checks. However, where data were not available, they assumed free flow speed in order to calculate route-level measures. According to Turner (2007), speeds below 5 mph or 5 km/h (about 3 mph) are deemed suspect by several ITS data systems.

VDOT's Traffic Monitoring System (TMS) has a robust program for monitoring the quality of Virginia's traffic volume information. Where traffic volume data are not available, VDOT applies some factoring (FHWA, 2013b). The unfactored VMT estimates are also carried through the calculation process in case there is a concern about overestimation of VMT. Turner et al. (2004) documented the data quality procedures used in the Urban Mobility Program, which have also been used in the UCR (FHWA, 2015b). However, these procedures pertain to the volume, speed, and occupancy data from the intelligent transportation system (ITS) detectors (loops, microwaves, etc.) and may not be directly applicable to the probe-based speed data. The UCR also mentions a data quality measure: percent of usable data (FHWA, 2015b). It is defined as the "the number of recorded data values divided by the number of total expected data values

(given the number of instrumented road sections, active sensors, and time periods).” According to Fekpe et al. (2004), there is no universal method for calculating adjustment factors for traffic volume calculations and most methods used by states are based on the TMG.

Contextual Details

The 2012 UMR (Schrang et al., 2012) focused on useful, national-level quantitative details of system performance measures. However, qualitative, contextual details are also necessary to make decisions. Several state performance measurement reports often provide such detailed contextual information along with the quantitative, analytical system performance results. Examples are WSDOT’s *Gray Notebook* (WSDOT, 2014) and *Corridor Capacity Summary* (WSDOT, 2013); the *Indiana Mobility Report* (Day et al., 2014; Remias et al., 2013); the *Maryland State Highway Mobility Report* (Mahapatra et al., 2013); and the MoDOT Tracker (MoDOT, 2013). The *Indiana Mobility Report* lists specific causal factors such as construction, bridge closure, snow storms, etc., that have had large effects on system performance. The *Maryland State Highway Mobility Report* presents VMT, corridor length, number of intersections, speed limits, etc. The MoDOT Tracker and WSDOT’s *Gray Notebook* go a step further to provide detailed stories of transportation system performance. The 2014 *Gray Notebook* tied the effect of a rebounding economy to the increasing congestion and “connected different dots” for readers. These contextual details provide additional information for identifying the underlying potential causes of the perceived transportation system performance, and hence the solution options available to pursue.

Visual Aids

As the number of performance measures and levels of analyses (both spatial and temporal) increases, visual aids are important tools for understanding the measures for decision making and for effectively communicating them to others. Aggregate numbers often do not convey the full spectrum of detailed information required for making local decisions. For example, a reliability index considering 80th percentile travel time will be unaffected by operational or traffic engineering improvements to improve the travel times below the 80th percentile mark. Therefore, notable new visual aids from the reviewed literature—beyond the traditional line graphs, bar charts, pie charts, and maps—are listed in Table 5.

The speed profiles in Figures 2 and 3 contain detailed legends explaining the visualizations. The speed profile packs in a lot of information by presenting the physical location of congestion, intensity of the congestion, and time periods by month when congestion occurred for the entire corridor and the entire year in one snapshot. The recurring bottlenecks and temporary bottleneck are easily visualized, along with “typical” congestion profile during rest of the year. However, one aspect of congestion that is missing is the time of day congestion occurred.

Table 5. Notable Visual Aids From Reviewed Literature

Figure No. ^a	Display Detail	Geographic Scope	Study/Reference
2,3	Speed profile	Corridor	<i>2012 Indiana Mobility Report</i> (Remias et al., 2013) used this for freeways.
4	PTI calendar, displaying PTI for the corridor for each day of the year	Corridor	<i>Maryland State Highway Mobility Report</i> (Mahapatra et al., 2013) used this for freeways.
5,6	Graphs of probability density function and cumulative density function graphs	Trip (O-D pair), corridor	<i>Establishing Monitoring Programs for Travel Time Reliability</i> (Institute for Transportation Research and Education, 2013) and <i>2012 Indiana Mobility Report</i> (Remias et al., 2013)
7	Reliability disks	Trip (O-D pair)	<i>Visual Analytics for Reliability</i> (Hranac, 2013)

PTI = planning time index; O-D = origin-destination.

^a Figure numbers refer to figures in the current report.

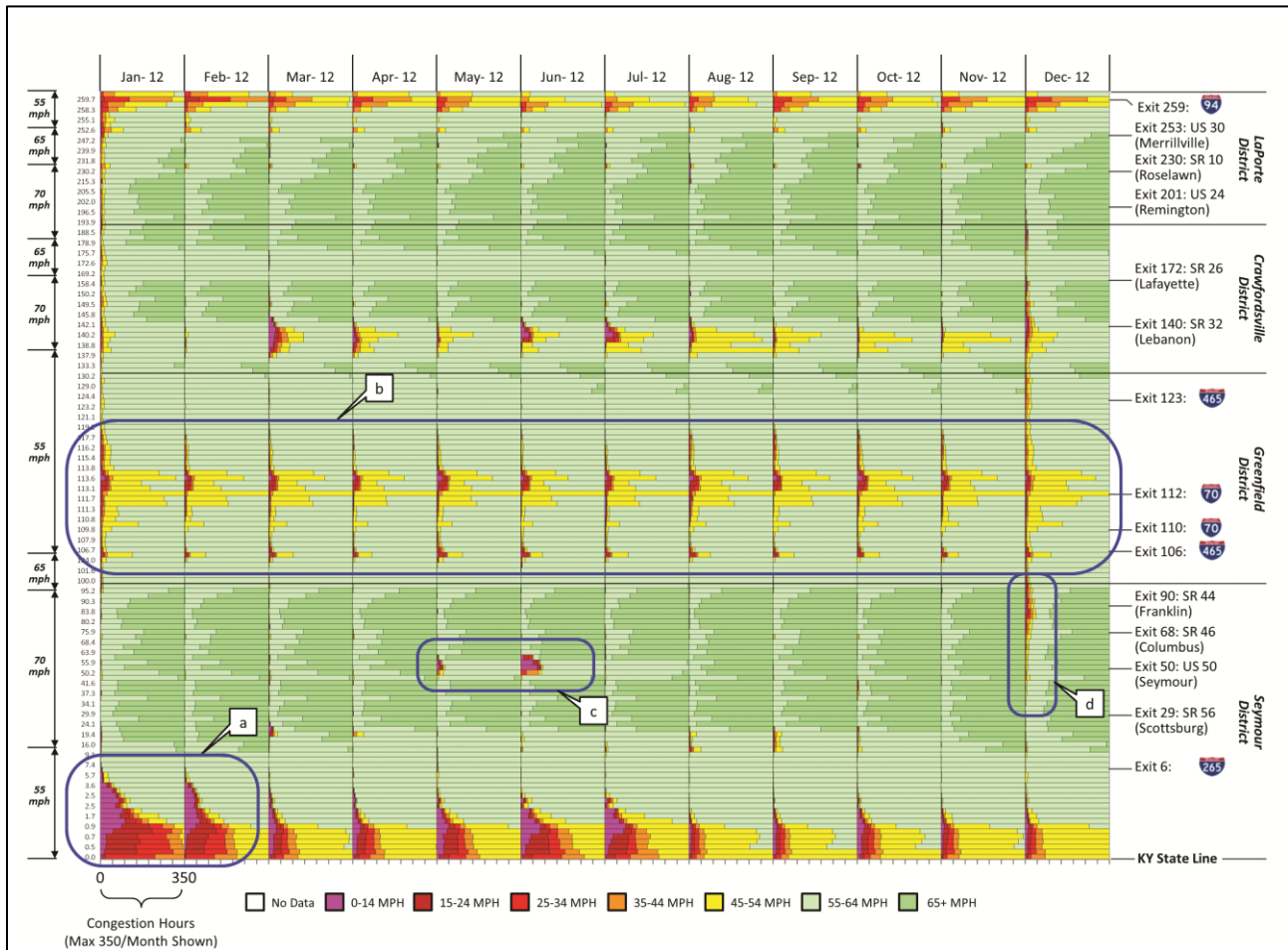


Figure 2. Speed Profile for a Corridor. From *2012 Indiana Mobility Report: Full Version* by S. Remias, T. Brennan, C. Day, H. Summers, E. Cox, D. Horton, & D. Bullock. Copyright 2013 by Purdue University. Reprinted with permission.

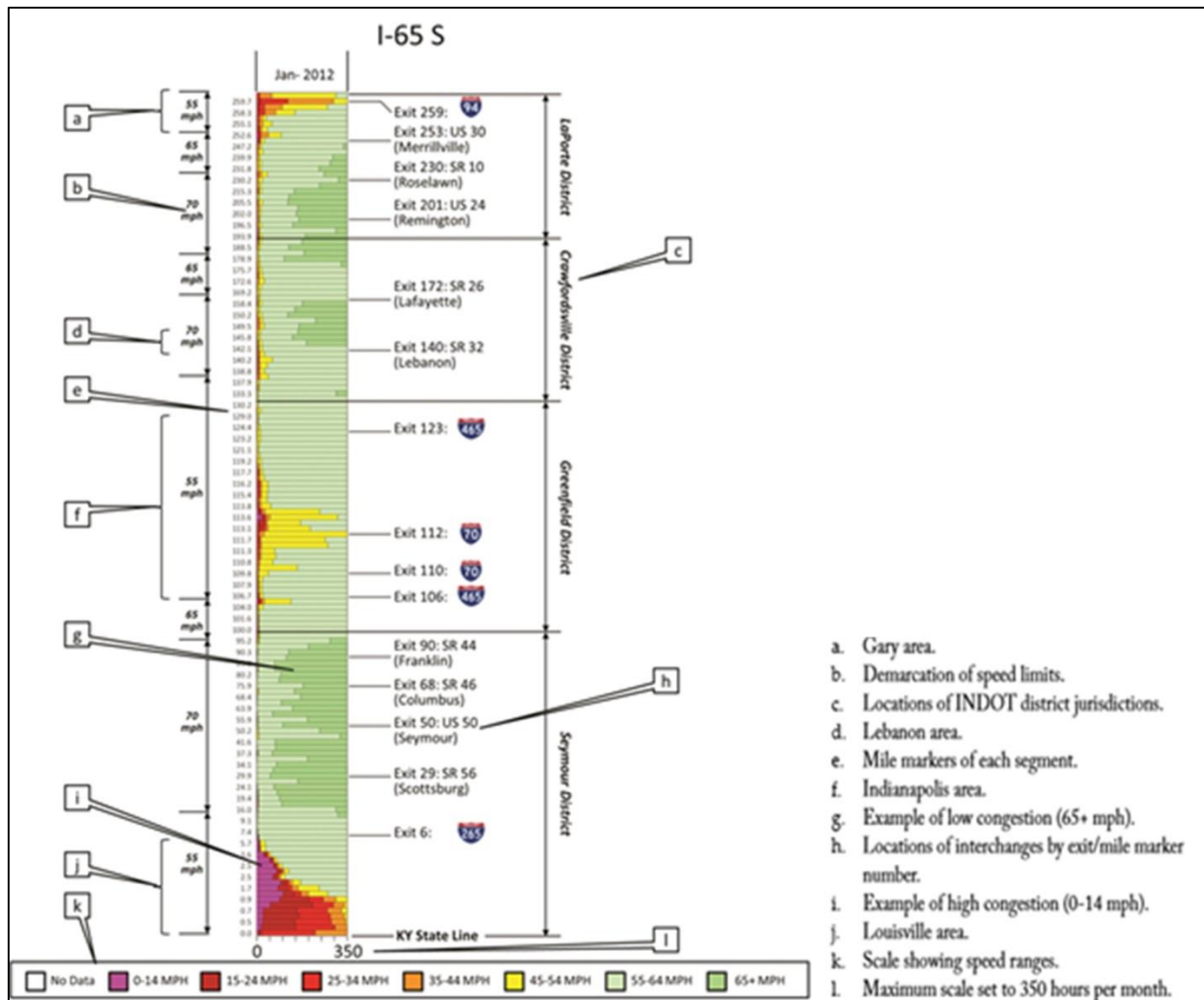


Figure 3. Explanations for the Speed Profile. From *2012 Indiana Mobility Report: Full Version* by S. Remias, T. Brennan, C. Day, H. Summers, E. Cox, D. Horton, & D. Bullock. Copyright 2013 by Purdue University. Reprinted with permission.

The PTI reported in Figure 4 for each day was calculated from the 95th percentile speed of the 1-minute records within the peak hour or peak period (M. Pack and A. Lund, personal communication) for a given corridor. This PTI is different from the day-to-day variations often presented in reports, considering the average speed from each day (and time of day) and the 95th percentile of these average daily speeds (for each time of day). Figure 4 essentially presents the variation within the day, rather than across the days.

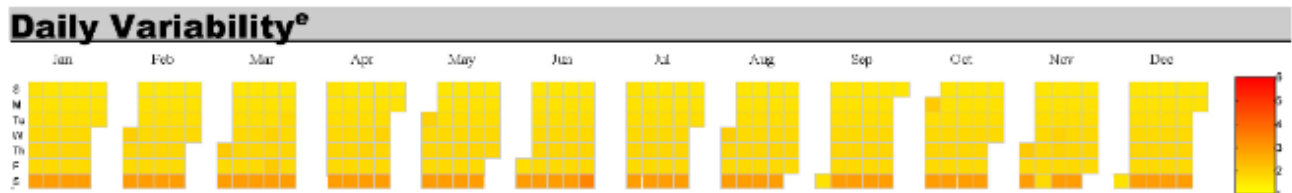


Figure 4. Daily Variability for an Entire Year Shown Using the Planning Time Index. From Mahapatra, S., Wolniak, M., Sadabadi, K.F., Beckett, E., and Jacobs, T. *2013 Maryland State Highway Mobility Report*. Maryland State Highway Administration, Baltimore, 2013. Reproduced with permission of Maryland Department of Transportation/State Highway Administration.

Figure 5 (probability density function) (PDF) and Figure 6 (cumulative density function) (CDF) comprise ways to communicate details of variations in the travel times along a corridor rather than presenting point statistics (such as average, 95th percentile speed, or standard deviation). The individual data points contributing to these graphs could be travel times from the entire day or a specific period (such as AM peak) for a longer analysis interval (such as a year). Figure 6 requires detailed event data (incidents, work zones, weather, etc.) associated with the travel time data. Understanding these details is often important to understanding the problem in more detail, identifying the right type of solution, and evaluating the impacts after project implementation. CDFs are also referred as cumulative frequency distributions (CFDs) in some literature. These recent studies on travel time data have extensively used CFDs and recommend their use for future studies.

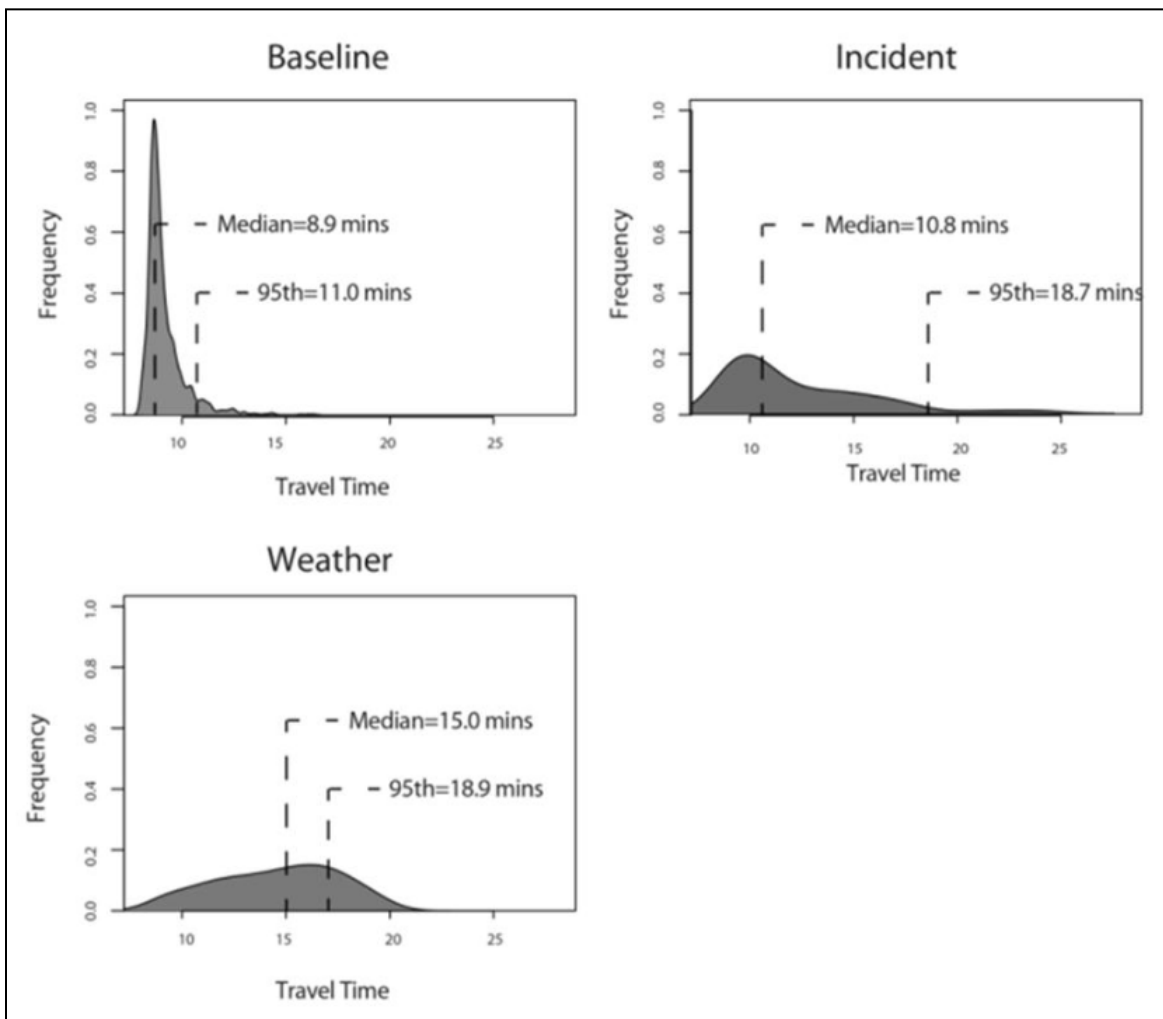


Figure 5. Probability Density Functions of Travel Times for Various Event Conditions. From *SHRP 2 Report S2-L02-RR-1: Establishing Monitoring Programs for Travel Time Reliability*, Figure 1.3, p. 10. Copyright, National Academy of Sciences, Washington, D.C., 2014. Reproduced with permission of the Transportation Research Board.

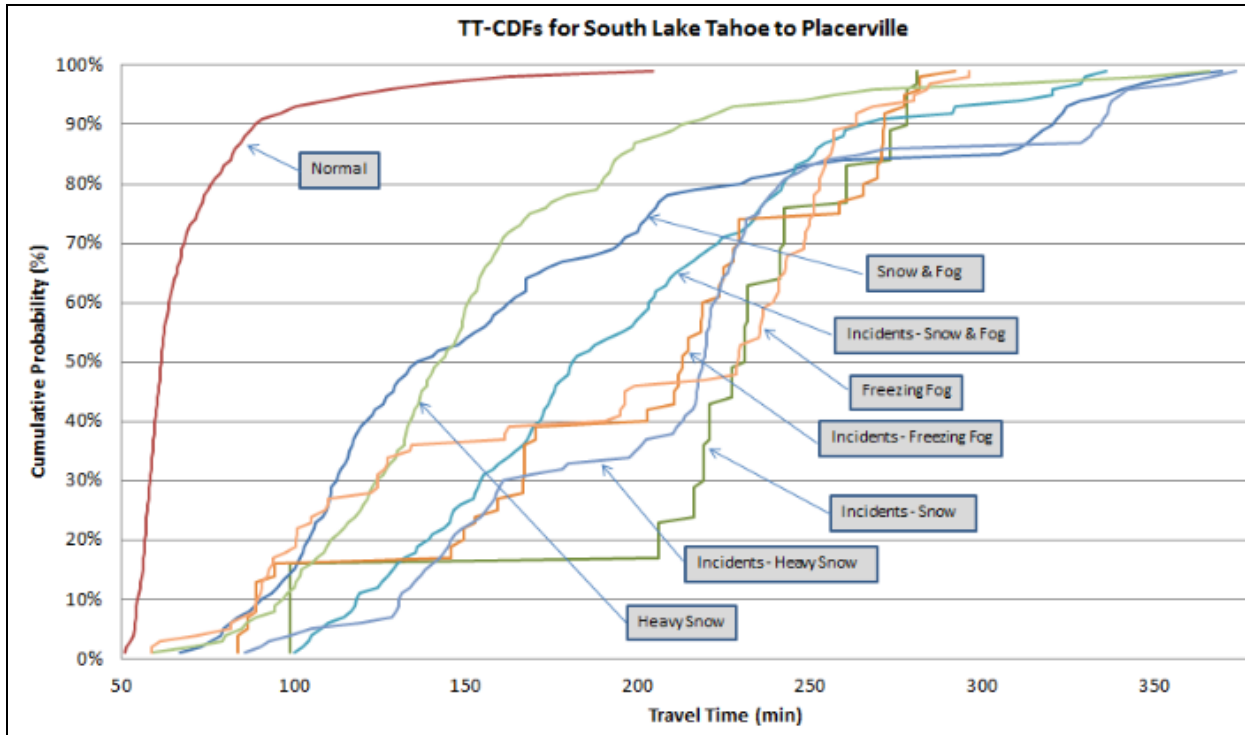


Figure 6. Cumulative Density Functions (CDFs) of Travel Rates for Various Regimes. From *SHRP 2 Report S2-L02-RR-1: Establishing Monitoring Programs for Travel Time Reliability*, Figure 3.7, p. 43. Copyright, National Academy of Sciences, Washington, D.C., 2014. Reproduced with permission of the Transportation Research Board.

Figure 7 is a novel representation of variability in travel times on a corridor across time of the day and over several days. The circular disk represents the 24-hour clock of each day. Each line represents the PDF of travel times for that time of the day across multiple days in the analysis period (say, 1 year), starting with zero travel time at the center and ending with very long travel times near the edge. The disk shows a wide range of travel times (flatter, unreliable) in the AM and PM peaks and sharper travel times (reliable) during off peaks, which are concentrated at the FFS. The graphic, developed in the software application Processing, is interactive and can be moved around to get a closer view of the details. One main disadvantage of this graphic is the 24-hour clock represented by the disk in contrast to the 12-hour disk familiar to most analysts and the audience.

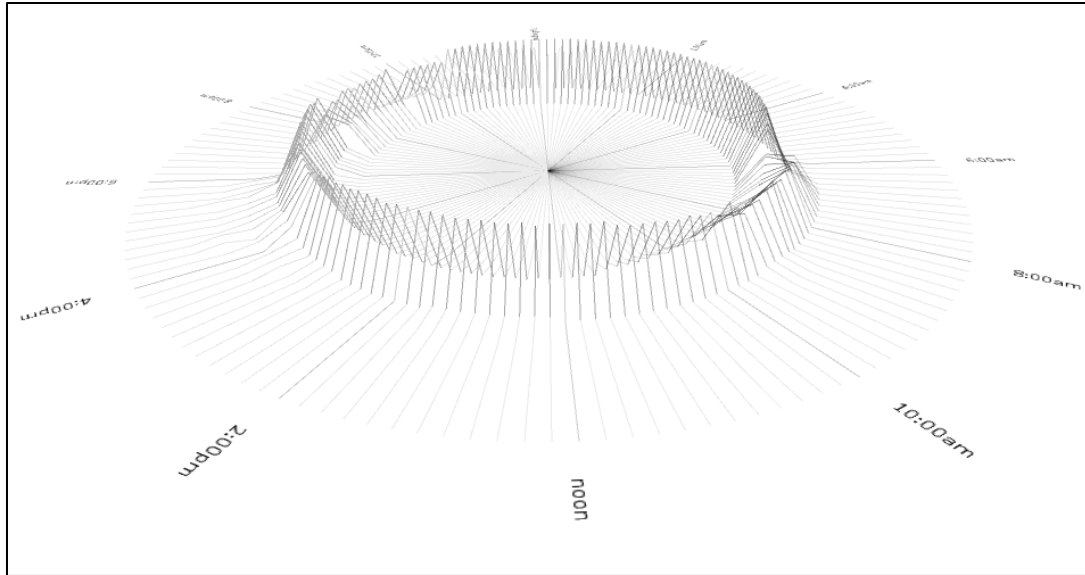


Figure 7. Reliability Disk Showing Travel Times From Multiple Days for a Corridor. Adapted from Hranac, 2013.

Relevant Topics Not Addressed in the Reviewed Literature

Relevant topics that were not addressed in the reviewed literature included the following:

- *Weekend traffic.* As noted in the 2012 UMR (Schrank et al., 2012), traffic delays have extended to weekends. Such high off-peak traffic delays are also noted in freight studies (U.S. DOT, 2014) and are especially important for recreational routes and for special events. However, the reviewed performance reports focused only on weekday peak period commuter traffic.
- *Non-recurring delay.* When travel speeds from several days (of the same day of the week) are averaged, the recurring, commuter, peak period delays will surface prominently whereas the non-recurring delays (from incidents, work zones, events, etc.) at other periods will get washed out. To calculate more accurate total annual delays, delays need to be calculated for each date and time first, which also requires more detailed, higher quality traffic speed and volume data.

Performance Measures Selected for This Study

The following performance measures were selected for this study with input from the TRP.

- *Delay.* For each time period of the day and day of the week, the average speed is calculated for the entire year for each segment and converted to average travel time. The difference between this average travel time and the congestion reference travel time (such as FFS) multiplied by the total VMT carried by that segment is the vehicle delay for that segment and time period. Truck speeds and VMTs are used to calculate truck delays. Delay from all time periods of the day is summed to get daily delay for

each segment. Delays from all the segments are summed to obtain the total network delay across all days of the week and multiplied by 52 to get annual network delay. This final value is divided by the network length to get delay per mile.

- *Travel time index (TTI)*. This is the ratio of average travel time to free flow travel time.
- *Planning time index (PTI)*. This is the ratio of the 95th percentile travel time to the uncongested (free flow) travel time.
- *AASHTO reliability index (RI80)*. The 80th percentile travel time for each time interval of the day is first calculated from the whole year of data. RI80 is the 80th percentile of these 80th percentile travel times divided by the free flow travel time. RI80 is calculated for either all days of the week or weekdays.
- *Congested hours*. If the average speed of a segment falls below a predetermined threshold, the segment is defined as congested for that period. The total number of hours for which each segment is congested is noted. The network congested hours for each time period is calculated by VMT weighting the congested hours at individual segments.
- *Congested miles*. Any segment that had congestion is counted toward congested miles if the congested hours are at least 2 hours in a peak period or 5 hours in the whole day (irrespective of whether the congested hours are contiguous or not). The network congested miles measure is the sum of the lengths of all congested segments.

Task 2 Results: Data Needed to Calculate Selected Performance Measures and Their Current Availability in Virginia

The main data elements needed to calculate all the system congestion and reliability measures identified in Task 1 are traffic volumes and speeds (or travel times) (Eisele et al., 2014). The sources of these data streams in Virginia, and their characteristics and data quality, are documented here. The other data elements needed, such as signal density, number of lanes, etc., are mostly static and need only to be updated from time to time.

The main source of traffic volume data in Virginia is VDOT's TMS, maintained by VDOT's TED. The TMS is unquestionably the most robust traffic counts program in the nation, with the highest number of working stations. According to the November 2013 *Traffic Volume Trends* (FHWA, 2013c), Virginia had the most continuous count stations (CCSs), on both rural arterials (278 stations) and urban arterials (351 stations). Texas and Florida have the next highest number of CCSs on rural arterials (113) and urban arterials (132), respectively. Many states have less than one-fourth of the stations Virginia has. Even so, it is noted that these data collection locations are point sensors. Data for other links or segments on the network must be estimated based on coverage counts, which may be collected as infrequently as every 5 or 6 years, and factor values. These annual growth factor values, seasonal factor values, and day of

week (DOW) factor values are already being calculated as part of the TMS. MPOs, counties, and cities may collect more frequent data on some of their local roads (such as through ITS equipment) or may have collected more recent data for specific projects. Using that information would enhance the traffic volume information from the TMS. TMS also provides more aggregated summary traffic volume information such as AADT and AADTT, which are required for segmenting the network.

Traffic volume information for CCSs is available at 15-minute intervals for each day of each year from VDOT's TED. There are 15 CCSs in or near the study network, as represented by the white dots in Figure 8. TOD traffic profiles for each day of the week can be derived from this detailed data set. For other TED links in the network, either appropriate growth factors have to be applied to the coverage count traffic profiles or an associated CCS should be identified. For this project, each link was associated with an available CCS based on a visual assessment of the similarities in available coverage count profiles and the CCS traffic profile. A more robust, scalable, semi-automated approach that can be applied to the entire state is to determine the correlation coefficients among the available profiles from the coverage counts and CCS and use the corresponding CCS profiles.

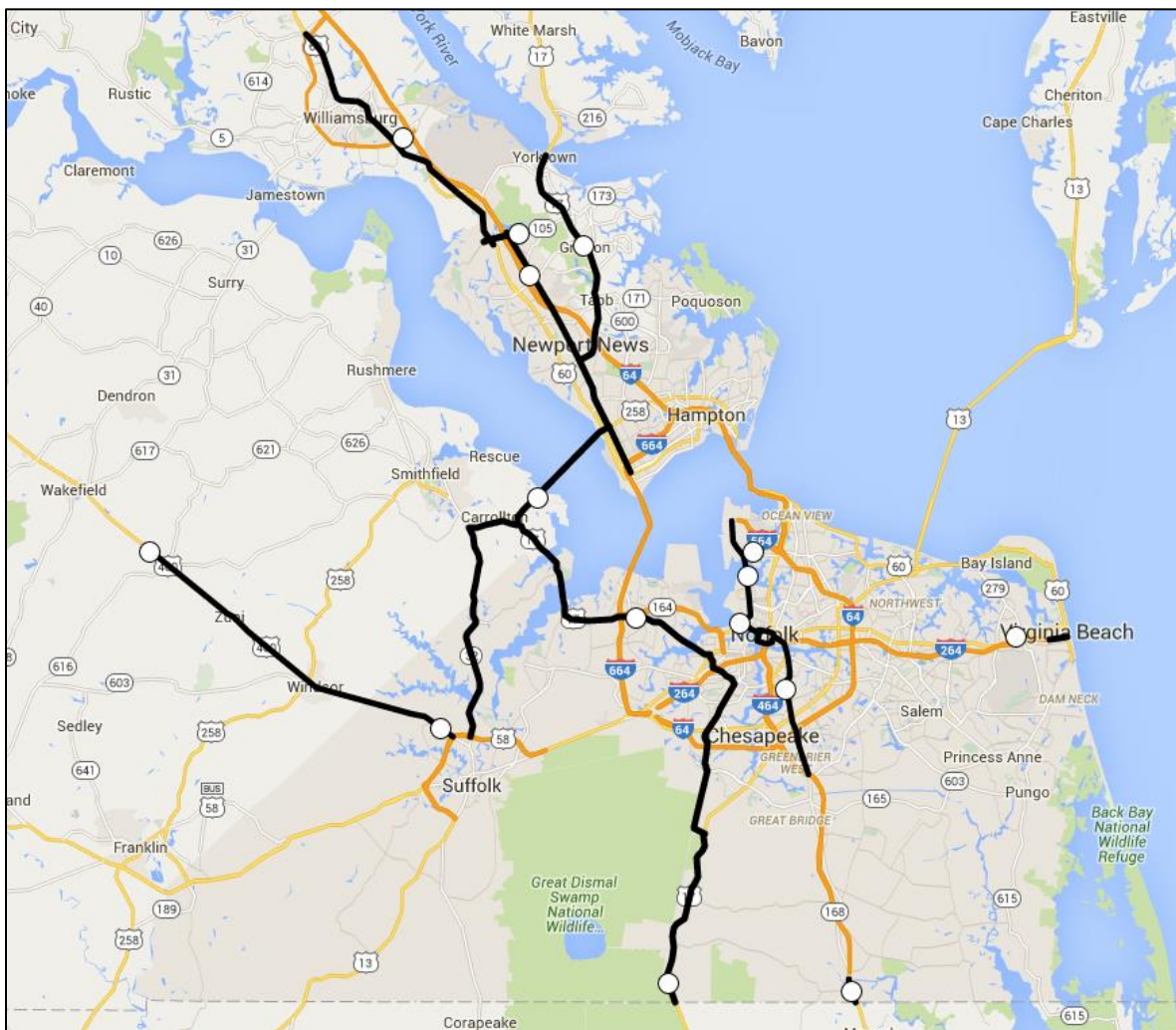


Figure 8. Study Network. Source: Google Maps.

Currently, the main source of speed data with vast coverage across Virginia is INRIX. VDOT has been procuring real-time INRIX speed data through the I-95 Corridor Coalition for a number of years. These data are available on many arterials at 1-minute intervals (for every day) for industry-standard spatial segmentation, i.e., TMCs. Singer et al. (2013), reporting on arterial travel time data collection technologies, mentioned 10 different technologies from the traditional inductive loop detectors to Bluetooth readers, emerging crowdsourcing approaches, and future connected vehicles. Various vendors currently provide such crowdsourced probe-based speed data, and no viable major technology alternatives with such a vast spatial coverage exist currently or are anticipated in the near future.

Since 2015, VDOT has started procuring INRIX data at a different spatial segmentation, called XD segments. These segments are defined by INRIX internally, provide finer granularity in many locations, and extend to many more roads in Virginia. Since these data were not available in 2013, they were not analyzed for this study. Potentially important considerations with this new segmentation, compared to the existing TMC data set, include the following:

- Data are more voluminous, given more spatial segments.
- The data quality could be higher in some locations owing to a higher resolution network. Data quality and quantity can also be lower in some locations owing to the lack of enough probes.
- In locations where XD segment end points do not match TMCs, XD segments may be more or less in alignment with NHS roads.
- Conflation with TMS links will have to be performed again.

The FHWA also procures average field-observed speed data (for passenger vehicles, trucks, and all vehicles) at 5-minute polling intervals from HERE and makes it available to state transportation agencies and MPOs as the NPMRDS (FHWA, 2013a). NPMRDS is also based primarily on crowdsourced, probe-vehicle data. NPMRDS is made available on a monthly basis, with data for the previous month. VDOT's Transportation and Mobility Planning Division (TMPD) was initially downloading these data, archiving them in an Oracle database, and providing access to them by VDOT staff. That was the data source for this study. However, NPMRDS data are also currently available through RITIS VPP Suite. NPMRDS also uses TMC segmentation. However, these TMC definitions are related to but different from the definitions used by INRIX. INRIX uses both internal (at an interchange or intersection) and external (between interchanges and intersections) TMCs; NPMRDS uses only internal TMC nomenclature that stretches across the span of both internal and adjacent external TMCs.

Periodically, VDOT also deploys Bluetooth monitoring (BTM) units along certain corridors to collect detailed travel time data to supplement or benchmark the data from other available speed data sources. Although BTM provides accurate speed data, its deployment costs much more than procurement of commercial, probe-based data. The quality of both Bluetooth and probe-based data depends on the availability of adequate sample sizes. In the study network, during 2013, BTM units were deployed at 12 locations along 15 miles of U.S. 17 for monitoring

and evaluating the adaptive signal control being deployed there. The 10 Bluetooth links were consolidated into eight segments (see Table 6) to align closely with the INRIX and NPMRDS TMCs. This filtered, paired travel time data for each vehicle between BTM units were downloaded from the website of the VDOT vendor (TrafficCast International, Inc., 2016). The outlier filtering algorithm used by the vendor is not known. However, visual inspection verified that obviously suspect data were not included in the downloaded files. Bluetooth data were collected for 6 months in 2013, from July through December. These Bluetooth data were used as the benchmark in this study. The 15 miles of Bluetooth links is referred as the benchmark network.

Known challenges with arterial probe-based data include the following:

- Whereas freeway travel time data seem to be of reasonable quality, based on a number of independent evaluations (e.g., Eisele et al., 2014; I-95 Corridor Coalition, n.d.), arterial travel time data have not received much scrutiny until now. Young et al. (2015) studied RITIS VPP arterial data in detail and provided guidelines on which arterials may have adequate data quality. The *Urban Mobility Scorecard* (Schrank et al., 2015) stated that INRIX used to discard very low speeds (such as 0 mph), which are often legitimate on arterials, and hence the data may be underestimating congestion.
- Some road segments do not have TMCs (e.g., parts of S.R. 168 and U.S. 60).
- Some road segments have overlapping TMCs (U.S. 17 and S.R. 143). These should be accounted for in the calculation of performance measures.
- The data are voluminous to download, process, analyze, and visualize. With 1,440 1-minute records per day per TMC and 309 TMCs in the study network, 1 year of INRIX data for the study network contained 162 million records. One year of 5-minute interval NPMRDS data for 203 TMCs would contain a maximum of 21.3 million records.
- Some TMCs are long (e.g., INRIX TMC 110+06033 in the study network is 8.2 miles long).

Other data elements potentially required for defining spatial segments and calculating system performance measures include roadway classification, speed limits, number of lanes, major interchanges and railroad crossings, type of signalization (pre-timed vs. coordinated vs. actuated), and signal density. The following sources were identified for these data elements:

Table 6. Bluetooth Segments

Dir.	Bluetooth						INRIX		NPMRDS	
	Link	Name	Length (mi)	Segment ID	No. of Signals	TMS Link ID	Length (mi)	No. TMCs	Length (mi)	No. of TMCs
SB	5830	Cook Rd.-Faulkner Rd.	1.6	1	4	50191	1.72	2	1.70	1
	5832	Faulkner Rd.-Ella Taylor Rd.	2.9	3	9	50193	2.61	4	2.65	3
	5834	Ella Taylor Rd.-Victory Blvd.	1.6	5	2	50196	1.59	3	1.45	2
	5836	Victory Blvd.-Commerce Cir.	1.1	7	7	653202	1.63	3	1.74	2
	5838	Commerce Cir.-I-64	0.7							
NB	5831	Faulkner Rd.-Cook Rd.	1.6	2	4	50191	1.71	2	1.70	1
	5833	Ella Taylor Rd.-Faulkner Rd.	2.9	4	9	50193	2.64	4	2.64	3
	5835	Victory Blvd.-Ella Taylor Rd.	1.6	6	2	50196	1.46	3	1.55	2
	5837	Commerce Cir.-Victory Blvd.	1.1	8	7	653202	1.79	3	2.12	2
	5839	I-64-Commerce Cir.	0.7							

Dir. = direction; TMS = Traffic Monitoring System; TMC = Traffic Message Channel; SB = southbound; NB = northbound; NPMRDS = National Performance Management Research Data Set.

- The NHS classification information for each roadway is available from the FHWA in the form of shapefiles (FHWA, 2015a). The current listing for Virginia states that 4,221 miles fall within the MAP-21 NHS designation. Identifying INRIX and NPMRDS TMCs that map to these roadways may require visual inspection and potential adjustments (where TMC end points do not match the NHS designation).
- Posted speed limits and information regarding number of lanes seem to be available from VDOT's Road Network System. Although these details can currently be viewed visually, it is not clear if this information can be easily exported for a large network as a simple text file. Even so, this information has to be conflated with the TMCs. For this study, this speed limit information was gathered from an inspection of the latest satellite imagery and road images from Google Earth and Google Maps Street View.
- Signalized intersections (and hence signal density information), railroad crossings, and interchange locations were obtained for this project from Google Earth and Google Maps Street View. Such information for all Virginia NHS segments will need to be manually collected or directly obtained from localities or other available sources.
- VDOT's TED has already conflated all the INRIX TMCs where speed data are available with VDOT's TMS links. Some adjustments to this conflation may be required through visual assessments and local traffic knowledge.
- TED TMS links need to be associated with nearby CCSs with comparable daily traffic volume profiles. For this study, TMS link coverage counts and average CCS data were plotted by time of day and TMS links mapped manually to CCS based on the similarity of these plots.

This study did not attribute causes to observed congestion. However, this is often required to develop countermeasures. Seven causes of congestion and unreliability were identified in the literature (U.S. DOT, 2014). Further, the Institute for Transportation Research and Education (2013) associated these causes with observed congestion regimes. Some of these causes (incidents, work zones, and weather events) are available in VDOT's Virginia Traffic Information Management System (VaTraffic) but are not tied to the underlying congestion. Further, VaTraffic currently focuses on freeways.

Temporal Coverage

For calculating annual delays and TTI, representative speed and volume data are required for each segment, from each month, day of the week, and time of the day. For calculating reliability measures (RI80, PTI), more detailed and high quality data are required for every single day of the year. If reliable data are not available for some days of a year (say, 20 days) for a segment, the reliability index could be significantly underestimated or overestimated.

Temporal Granularity

The reviewed literature mainly used or recommended three aggregation intervals:

1. *15 minutes*: HCM 2010 (TRB, 2010); Wikander et al. (2014); Pu (2013); 2012 UMR (Schrank et al., 2012) for PTI
2. *1 hour*: Turner and Qu (2013); AASHTO (2012) for delays; Liao, 2013; HCM 2010 (TRB, 2010); 2012 UMR (Schrank et al., 2012) for TTI; RITIS VPP Suite (UMD CATT Lab, n.d.)
3. *Peak periods*: different definitions exist in the reviewed literature (Table 7).

AASHTO SCOPM (AASHTO, 2012) methodology used 5-minute speeds for calculating a reliability index. The UCR (FHWA, 2015b) also used 5-minute data for calculating congested hours, TTI, and PTI. Pu (2013) used raw probe data, 1-minute aggregation, and 5-minute aggregation and reported insignificant differences for the measures calculated from 1-minute and 5-minute data. JMT Technology Group and VHB (2012) used 5-minute speeds, often averaged up to peak period speeds. For operational analyses, HCM 2010 (TRB, 2010) recommended using aggregation intervals of at least 15 minutes (to avoid unstable, short-period fluctuations) but not longer than 1 hour (so as not to miss important stable demand surges).

Turner and Qu (2013) reported PTI for the peak periods and for the whole day. Although the selection of one AM and one PM peak period for the entire state would make calculations easier, the results might not be meaningful, especially when both urban and rural areas are considered.

Table 7. Definitions of Peak Period From Reviewed Literature

AM Peak	PM Peak	Reference
6–9 AM	4–7 PM	Turner and Qu (2013); AASHTO (2012); Keenan et al. (2012)
5–10 AM	2–7 PM	Liao (2013)
6–10 AM	3–7 PM	2012 UMR (Schrank et al., 2012)
8–9 AM	5–6 PM	Peak hours (Mahapatra et al., 2013)
5–10 AM	2–8 PM	<i>Corridor Capacity Summary</i> (WSDOT, 2013) for congested segments
6–9 AM	3–6 PM	For transit peak hours
6–9 AM	3–7 PM	For person throughput at specific points on a corridor
Different period for each corridor		JMT Technology Group and Vanasse Hangen Brustlin, Inc. (2012). VDOT identified these different peak periods based on speed plots, volume plots, and local knowledge.

WSDOT = Washington State Department of Transportation.

Task 3 Results: Calculation and Analysis of Selected Performance Measures for a Sample Network

Defined Study Network

The study network was defined in conjunction with the project's TRP. Figure 7 and Table 8 present details of this network, which is in the Hampton Roads region. It is composed of 288 directional road miles and is represented by a total of 309 TMCs in INRIX data and 213 TMCs in the NPMRDS.

The selected routes include the following diverse aspects, enabling reasonable extension of the results to the rest of Virginia:

- *NHS functional classes:* MAP-21 principal arterial, Strategic Highway Network (STRAHNET) route, STRAHNET connector, intermodal connector
- *Traffic patterns:* urban/suburban/rural, recreational/seasonal, and commuter traffic
- *Number of lanes:* 2, 4, and 6 (both directions)
- *AADT:* 2,100 to 73,000 (both directions)
- *Percentage of trucks:* 1% to 17%
- *Directional traffic (peak traffic percentage in peak direction):* 50% to 75%
- *Speed limits:* 25 to 55 mph
- *Corridor length:* 0.5 to 63 miles
- *Signal density per mile:* 0-5 (considering link lengths of 1 mile or longer)
- *Intersections:* signalized (coordinated and isolated), unsignalized, and grade-separated interchanges
- *Other notable aspects of the selected network:* school speed zones, railroad crossings, end of freeway, and bridges.

Table 8. Study Network Details^a

Route/ Corridor	Centerline Miles	Total No. of Lanes	AADT ^b	Speed Limit (mph)	Signal Density (per mile)	Number of INRIX TMCs				Additional Characteristics
						NB	SB	EB	WB	
U.S. 17	61.8	4-6	4,300-50,000	35-55	0-5.4	66	66			Urban and rural segments; several bridges; state border
U.S. 60	17.3	2-4	8,100-22,800	40-45	0.5-3.6			15	15	Tourist/recreational route; MAP-21 principal arterial
S.R. 10/ U.S. 258	15.3	2-4	9,400-24,300	45-55	0.6	8	7	2	3	Rural undivided
S.R. 143	14.6	4-6	10,800-73,000	25-45	2.6-4.2			14	14	Congested suburban commute corridor
U.S. 460	14.9	4	11,200-19,200	35-55	0.1-0.8			8	8	Rural undivided; heavy truck traffic
S.R. 337	10.6	4-6	2,100-34,900	30-35	2.1-5.7	16	16	7	6	Urban, downtown streets
S.R. 166/168	9.6	4	20,000-56,600	30-55	1.1-3.9	11	10	4	4	Urban and rural; intermodal connector; other NHS and MAP-21 principal arterial; end of freeway; tourist/recreational route; state border
S.R. 105	1.3	4	23,400-39,200	45	-			3	3	STRAHNET connector; limited access; divided
22nd/21st	0.5	6	10,500-13,100	25-35	-			2	1	Urban; other NHS; end of freeway; tourist/recreational route

AADT = annual average daily traffic; TMCs = Traffic Message Channels; NB = northbound; SB = southbound; EB = eastbound; WB = westbound; MAP-21 = Moving Ahead for Progress in the 21st Century Act; NHS = National Highway System; STRAHNET = Strategic Highway Network.

^a Data from 2013.

^b Rounded to the nearest 100.

Calculation of Performance Measures

Detailed calculation steps for different measures from Task 1 were presented previously. A consolidated overview of the entire calculation methodology with different options is presented here (see Figure 9) to explain in detail how the various calculation options were analyzed. The steps in the calculation methodology are connected with arrows and explained here. The other rectangular shapes provide additional details for those steps. Some steps include details that may be unfamiliar to some readers. Such details are also described here to improve comprehension.

A full year data set of traffic speed or volume for the study network contained millions of rows and required use of appropriate software tools. Statistical Analysis System (SAS) software was used in this study to read data, calculate measures at different spatial aggregations, and generate preliminary graphs. The full data set was too large for even SAS. The code was therefore developed to analyze data for each corridor separately and looped across corridors to generate higher spatial level measures. The final results from SAS for all the investigated calculation methodologies were analyzed together and graphed in Microsoft Excel and Tableau.

Step 1: Set Calculation Options

The following calculation parameters and most options were selected with input from the TRP. One option each, for a total of 11 calculation parameters, was set for each run of the SAS code.

These parameters and their options included the following:

1. *Speed data source.* There were three options: INRIX, NPMRDS, and Bluetooth.
2. *Volume profile method.* There were two options: local CCSs, and the Texas A&M Transportation Institute's method in the *2015 Urban Mobility Scorecard (UMS)* (Schrank et al., 2015). For the first option, each HPMS link was associated with a nearby CCS based on correlation of the available time-of-day (TOD) volume data. For HPMS links, volume data are available for about 2 days, at a 15-minute aggregation, from a 3-year period. The UMS uses national average traffic volume profiles based on extensive past research. Details of the UMS method are presented in Appendix A.
3. *Vehicle mix.* There were three options: all vehicles, trucks (Class 5 and above), and trucks (Class 6 and above). CCS volume data are available by vehicle class. The impact of the definition of "truck" in terms of vehicle classes on the measures was of interest to this study.
4. *Data quality.* There were two options for INRIX data: confidence score 30 and all available data. Each INRIX speed record contains a value for the confidence score: 10, 20, or 30. Whereas score 30 records contain real-time information, records with scores of 10 or 20 are derived from historic information when not enough real-time information is available.

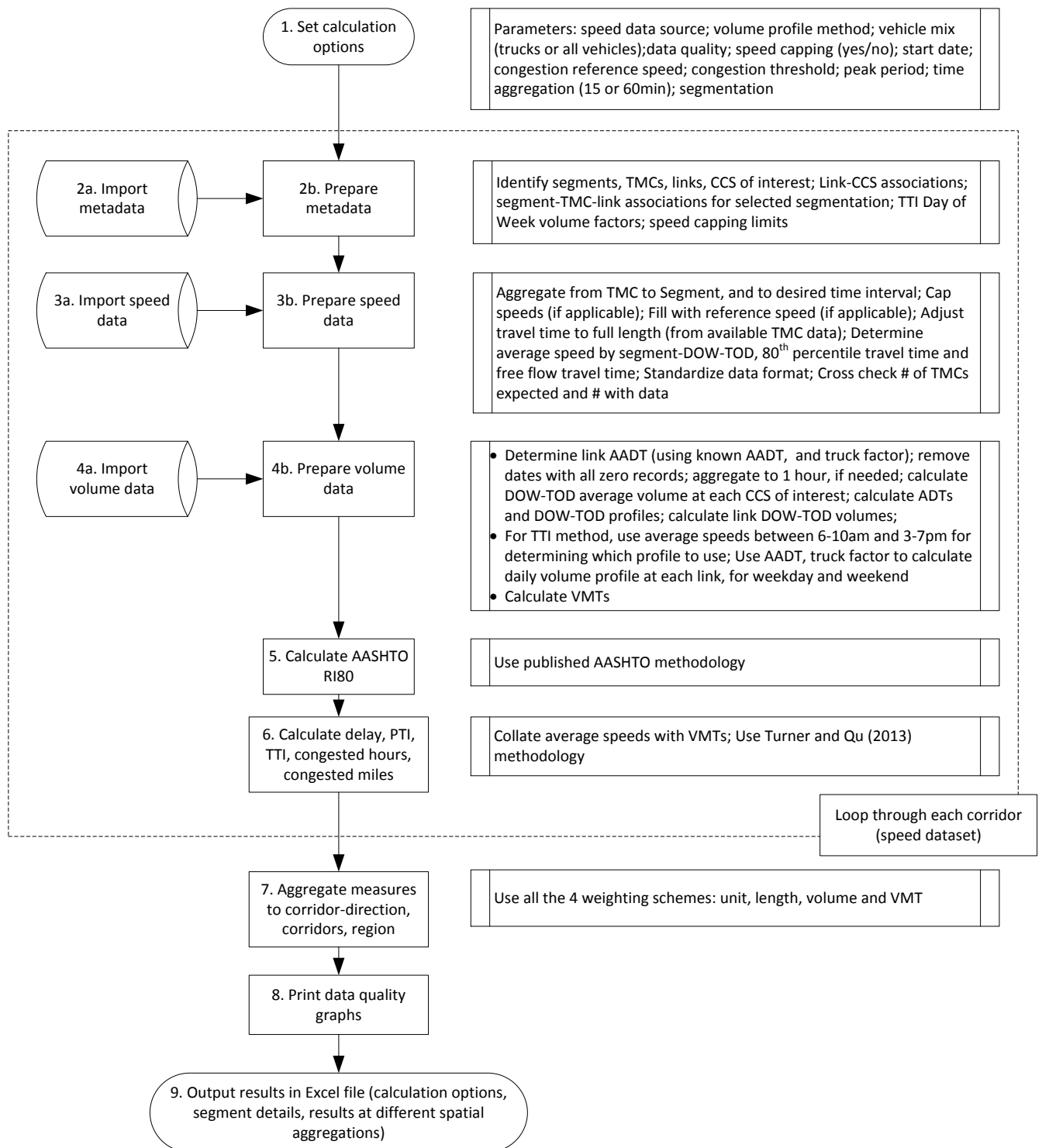


Figure 9. Flowchart of Calculation Methodology. CCS = continuous count stations; DOW = day of week; TOD = time of day.

5. *Speed capping.* There were two options for capping NPMRDS data: yes and no. NPMRDS records contain a number of outliers at both low and high speeds. In this study, speeds were capped on the lower end at 3 mph and on the higher end at 10 mph over the speed limit. Any speed falling within this range was retained as is.
6. *Start date.* There were two options: January 1, 2013, and July 1, 2013. NPMRDS data were available only from July 2013. To afford direct comparison, INRIX and Bluetooth data were also analyzed with the same 6 months of data. For comparing annual measures, the full year data were used for INRIX and Bluetooth.
7. *Congestion reference speed.* There were three options: INRIX reference speed (only for INRIX data), PSL, and daytime LTS. *Daytime LTS* is defined as the average of the fastest 2 hours during the daytime hours, 6 AM to 8 PM, from the annual average speed profile for each day of the week.
8. *Congestion threshold.* There were four options: 0.6, 0.7, 0.8, and 0.9. Congestion threshold is multiplied by congestion reference speed to obtain congestion threshold speed. If the average speed at a TMC for a time period falls below the congestion threshold speed, that TMC and time period is defined as congested traffic for calculating delay, congested hours, and congested miles measures.
9. *Peak period definition.* There were two options: 5 to 10 AM and 6 to 9 AM for the AM peak, and 2 to 8 PM and 3 to 7 PM for the PM peak. These definitions affect only the peak period measures.
10. *Time aggregation.* There were two options: 15 minutes and 1 hour. CCS volume data are available at a 15-minute interval. Speed data are available at a 1-minute interval from INRIX, a 5-minute interval from NPMRDS, and as individual probe vehicles (recorded at 1-minute time stamps) from BTM. Although 15-minute aggregation is more precise and in line with traditional operational analyses (HCM 2010) (TRB, 2010), 1-hour aggregation involves faster analyses, less data storage, and less cost.
11. *Segmentation.* There were four options: TMC, custom, entire corridor, and Bluetooth segments. The study network was divided into segments, the smallest spatial units defined for calculating performance measures. This process is called segmentation. Three main segmentations were used in this study: TMCs, custom segments, and entire corridors. The first approach defined each TMC as an individual segment. In the second approach, approximate rules of thumb based on roadway and geometric attributes were developed to define segments based on the literature review and discussions with the TRP. One reason attributes were not used as objective thresholds for segmentation was that many attributes change from year to year and network performance measures need to accommodate such changes in attributes and segmentations. In the third approach, each corridor along one direction, irrespective of length, was defined as a segment.

The following rules of thumb with regard to custom segmentation were developed and used in this study:

- Segments did not go across grade-separated interchanges and major intersections (with 4- to 6-lane crossing roads). These points are often sources and/or sinks of high traffic volumes, even if AADT is comparable on either side of the crossing.
- Lane drops and additions, which are indications of bottlenecks and major traffic volume changes, were used as segment boundary points.
- AADT difference at adjacent TMCs is more than 10,000.
- Signal density difference between adjacent TMCs is not too high. In urban areas, signal density is often about 4 or 5 signals per mile, and in rural areas, it is below 4, and often 0.
- Segment lengths were not too long or too short. Urban segments were typically kept small (less than 3 miles), since traffic volumes change at mid-block accesses and turning movements. Rural segments were as long as 10 miles because of the lack of such drastic volume changes. INRIX uses internal and external TMCs. The former are very short, on the order of 0.1 or 0.01 miles. Even if AADT at an internal TMC was very different from that at the nearest external TMC, the two TMCs were combined to avoid very small segments.

The fourth segmentation option followed the locations of BTM units.

Step 2: Import and Prepare Metadata

Each TMC is associated with a corresponding HPMS link and designated as part of a segment. This process of association is called conflation. Given the four segmentations of interest to this study, two definitions of TMC (INRIX and NPMRDS), and three speed data sources (INRIX, NPMRDS, and Bluetooth), individual metadata files were created for each valid combination of segmentation, TMC definition, and data source.

Each HPMS link was also manually associated with a CCS for inheriting the TOD traffic volume profiles. This association was determined by visual examination of the TOD volume profile of the short counts at each link and the average TOD profile at the nearby CCSs based on peak traffic direction and the ratio of peak period traffic volume to AADT. The study network contained a total of 185 links (by direction) and 21 CCSs (by direction). The INRIX TMCs, NPMRDS TMCs, and Bluetooth links were all conflated with corresponding HPMS links using metadata (start, end points) and visual examination of maps. The number of signals within each TMC or Bluetooth link was counted using Google Earth and Google Maps Street View. PSLs were obtained from VDOT's Road Network System and supplemented or cross-checked using Google Maps Street View images.

UMS DOW and TOD profile data, provided directly by the Texas A&M Transportation Institute, were also imported into SAS in Step 2.

Step 3: Import and Prepare Speed Data

In this step, the appropriate speed data were imported into SAS and aggregated to the desired time interval selected in Step 1. In the case of INRIX, the data set was too large to analyze together. Therefore the analysis was performed on a corridor-by-corridor basis. Segment travel times were calculated by summing the travel times from the available constituent TMCs. Segment speeds were calculated as the travel time divided by the summed lengths of constituent TMCs with available data. NPMRDS speeds were capped in this step, if needed. INRIX speed data quality rules were applied as set in the options in Step 1.

For calculating traffic annual delays, an average speed from the entire data set is required for each segment, day of the week, and time of day. Wherever no average speed was available, these steps inserted the segment reference speed, calculated in manner similar to that for segment speed from the constituent TMCs. For each segment, DOW, TOD, and the 80th percentile travel times were also calculated in these steps.

INRIX data for the entire year of 2013 were downloaded from RITIS VPP Suite (UMD CATT Lab, n.d.). INRIX data were downloaded as 1-minute intervals and included TMC, speed, reference speed, and confidence score. NPMRDS data were downloaded from the VDOT TMPD's archive database. NPMRDS data are available at 5-minute aggregations and include TMC, mixed-traffic speed (which is the average of all available speeds), car speed, and truck speed. Bluetooth raw data (each vehicle pair) for the entire year of 2013 were downloaded from the website of the VDOT vendor (TrafficCast International, Inc., 2016). TrafficCast is the vendor that deployed the BTM units on the roadway and collected, performed outlier screening of, and archived the data. Bluetooth data were screened by the vendor to remove outliers. Table 6 provides Bluetooth link and segment details.

Step 4: Import and Prepare Volume Data

Traffic volumes for the CCSs and HPMS links were obtained from VDOT's TED. The AADT data for each HPMS link and the entire volume data set for CCS are prepared and imported in these steps. Volumes are aggregated to 1-hour intervals if needed. For the local traffic profiles method, the volume data at CCS are averaged for each day of the week and time of day, and the traffic volume observed for each time interval as a fraction of the AADT is calculated. Based on these CCS profiles, link-CCS associations from Step 2, link AADT, and truck factor (for truck measures), link TOD traffic volume profiles are constructed.

For the UMS profiles method, 1 of the 16 national average traffic volume TOD and DOW profiles is used. The method for selecting the profile for each TMC is presented in Appendix A.

Finally, segment VMT profiles are calculated by summing the product of constituent link volumes and lengths.

Steps 5 and 6: Calculate Segment Measures

Published procedures are used to calculate the segment measures and are explained in detail in the Task 1 results and Appendix A.

For calculating NPMRDS truck performance measures, truck speeds (or travel times) were used wherever available. If truck speeds were not available, all vehicle speeds were used. If all vehicle speeds were also not available, the speed limit values were used. INRIX does not provide separate truck speed data. Therefore, the same speed values were used for all vehicle performance measures and truck performance measures.

Step 7: Aggregate Measures to Higher Spatial Features

The segment level performance measures were aggregated to higher spatial features such as corridor and region using weights. These weights were defined in conjunction with the TRP. To sum regional delay from segment delays, the use of either “number of vehicles” or “number of persons” for weights is meaningful, since delays occur for both vehicles (as in calculating the fuel usage and emissions) and persons (as in calculating motorist frustration and loss of productivity). However, such clear meaning is not the case in calculating average regional reliability performance measures. If reliability is considered to be a characteristic of the facility, weighting by segment lengths is meaningful. If reliability is considered to be a characteristic of the traffic and “experienced” by the vehicles or motorists, weighting by number of vehicles or persons is meaningful. Even if it is agreed that the latter approach is more appropriate, a network can possibly be segmented in such a way that the final statewide unreliability value looks as small or as large as the analyst desires. For these reasons, the following four weights were investigated in this study:

1. *Unit weight or no weight.* Each performance measure at each constituent segment was simply averaged. Measures at the constituent segments were added and then divided by the total number of segments.
2. *Length.* Segment lengths were used as weights.
3. *Volume.* Average annual traffic volume at each segment was used as a weight.
4. *VMT.* Segment volume multiplied by length was used as a weight.

Weights were not selected as options for each SAS code run. Instead, aggregate measures were produced using all the four weights for each run.

Steps 8 and 9: Output Data Quality Graphs and Export Results

Data quality graphs and tables were printed in this step to cross-check that the data and calculations were valid. Due diligence data quality visual assessment tests developed from the reviewed literature and used in this study are listed in Appendix C. All results were exported from SAS to Microsoft Excel for further analyses.

Analysis of Performance Measures

First, the quantity and quality of INRIX and NPMRDS data were analyzed. For quantity, for all TMCs or Bluetooth segments, the number of data points available was compared to that expected, at 15-minute aggregations, for the entire day and for the daytime period (5 AM-9:59 PM). The expected number of records per spatial unit per day was 96. This was multiplied by the total number of spatial units (TMCs or Bluetooth segments) and number of days of analysis (July 1–December 31, 2013). Sources were also analyzed by filtering outliers. For INRIX data, outliers were defined as data records with a confidence score of 10 or 20. For NPMRDS data, outliers were defined as speeds more than 10 mph above the speed limit and speeds below 3 mph. For quality, four more analyses were performed:

1. For each TMC, the TOD traffic patterns were visually examined as averages and across all the dates. TMCs in congested areas usually have a weekday TOD pattern, often with reduced speeds during the peak periods and steady high speeds in the nighttime. In low traffic areas, speeds may remain consistently high throughout the day.
2. The standard deviation of the data across all dates was plotted by time of day.
3. CFDs were plotted and evaluated for all data sources.
4. Performance measures were calculated using both data sets and compared with the measures calculated using the Bluetooth data on the benchmark network.

Second, the SAS code was run with different calculation option selections to investigate the impact of the options on the final measures. For example, the code was run two times with the following speed data source selections: once with INRIX and once with Bluetooth. The final results from these two runs were then compared to investigate the effect of speed data source. The analysis focused on select impacts and not a full design of experiments across all the calculation parameters and options. Interesting cases, determined in discussions with the TRP, were explored. Given the large number of parameters and options, statistical significance tests were not the focus of this study. Instead, the focus was exploratory analyses.

Third, the impacts of the four weighting factors on each measure were investigated, along with correlations among the different measures.

Fourth, performance measures and calculation options were analyzed across the following four geometric and traffic factors: AADT, signal density, speed limit, and segment length.

Data Availability and Quality Analysis

Results from the data availability analyses are presented in Table 9 and Figure 10. For calculating these percentages, the numerator was the actual number of records in the data and the denominator was the expected number of records. All data sources were analyzed at 15-minute

aggregation intervals. Therefore, the expected number of records was total number of days multiplied by 96 (number of 15-minute intervals per day) and number of TMCs/links. Although INRIX provided a near-complete set of records for the whole day, when filtered by confidence score (only 30), the data availability dropped below 50%. Percentages for NPMRDS records were 39% before filtering and 34% after filtering for the whole day. NPMRDS truck data were available for 5% of the time (across all TMCs, dates, and 15-minute intervals). These findings are also in line with a white paper on data quality prepared by Cambridge Systematics, Inc., and Texas Transportation Institute (2015). Just above 1% of NPMRDS records (both all vehicles and trucks) were less than 3 mph, and 6% of all vehicle speeds and 12.5% of truck speeds were more than 10 mph above PSL. It should be noted that these static thresholds of 3 mph and PSL + 10 mph are sample filtering approaches in line with the reviewed literature and provide an idea of data quality. Segment speeds beyond these thresholds are possible in reality during incidents, weather events, or free flow conditions such as at nighttime or on rural roads.

For each 15-minute interval time of the day, the standard deviation of speeds across days was around 10 mph for NPMRDS data. This value is about 2 to 3 times the standard deviations with the BTM and INRIX speed data sets, which were around 3 to 5 mph.

For all the three data sources, daytime (5 AM-10 PM) filtered data availability was about 15% higher than during the whole day. Therefore these data sets are more suitable for analyzing recurring traffic congestion during daytime rather than nighttime work zones or special events.

Table 9. Data Availability by Data Source, Time Period, and Filtering

Time Period of Day	Bluetooth	INRIX	NPMRDS
Full day	-	98%	39%
Full day filtered	60%	47%	34%
Daytime (5 AM-10 PM) filtered	76%	61%	48%

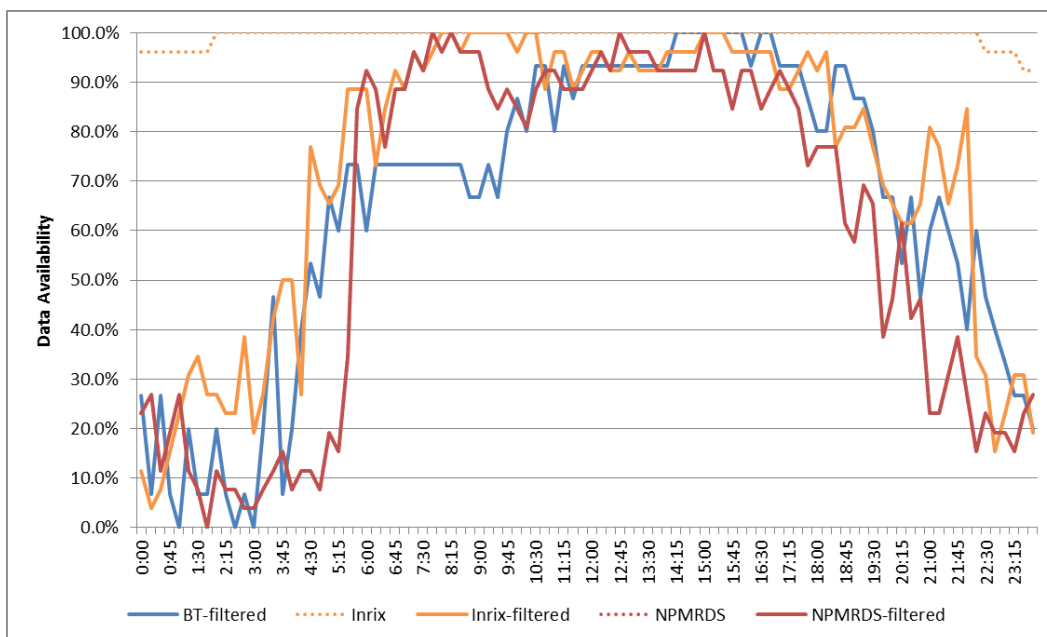


Figure 10. Data Availability by Time of Day and Source for Bluetooth Segment 7

Figure 10 presents the data availability by time of day for each source for Wednesdays in the July 1–December 31, 2013, analysis period for one segment (Segment 7). The average segment speeds and standard deviations for this analysis period are presented in Figures 11 and 12, respectively. Although data availability for all three sources were comparable, i.e., high during the daytime and low during the nighttime, the average daytime NPMRDS speeds were slightly lower (about 5 to 10 mph) than for the other two sources. The standard deviation of the NPMRDS data is also high across the day compared to those of Bluetooth and INRIX. This high standard deviation was also the case in the sample CFD for all data sources for 8 AM in Figure 13. NPMRDS data displayed higher variation and lower speeds compared to Bluetooth and INRIX data. CFDs can be constructed with travel time, travel rate, or speed on the X-axis. Travel rate and speed account for differences in length across the data sources. Figure 14 presents the day-to-day variation of the TOD speed patterns and illustrates the high standard deviation in NPMRDS data. The recurring traffic pattern is more readily visible for Bluetooth and INRIX speeds, whereas NPMRDS speeds seem more random.

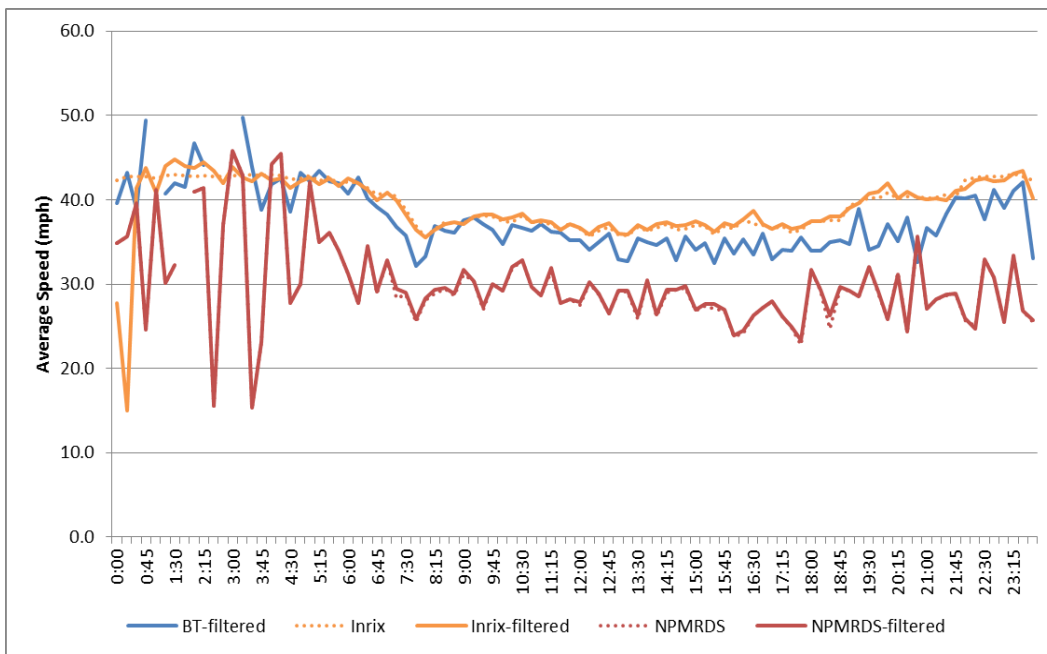


Figure 11. Average Speed by Time of Day and Data Source for a Sample Segment

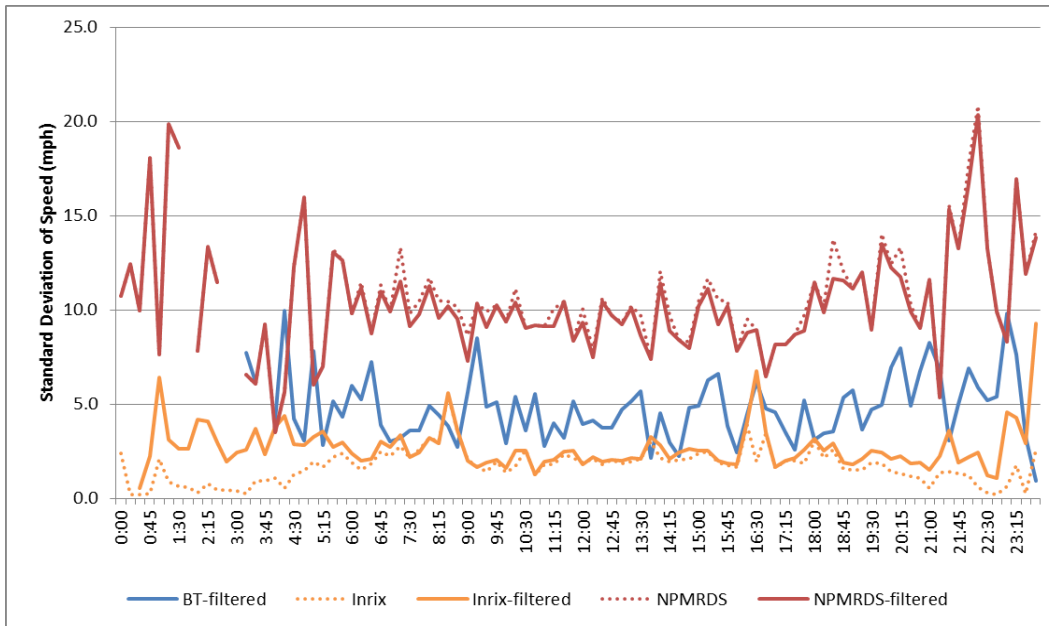


Figure 12. Speed Standard Deviation by Time of Day and Data Source for a Sample Segment

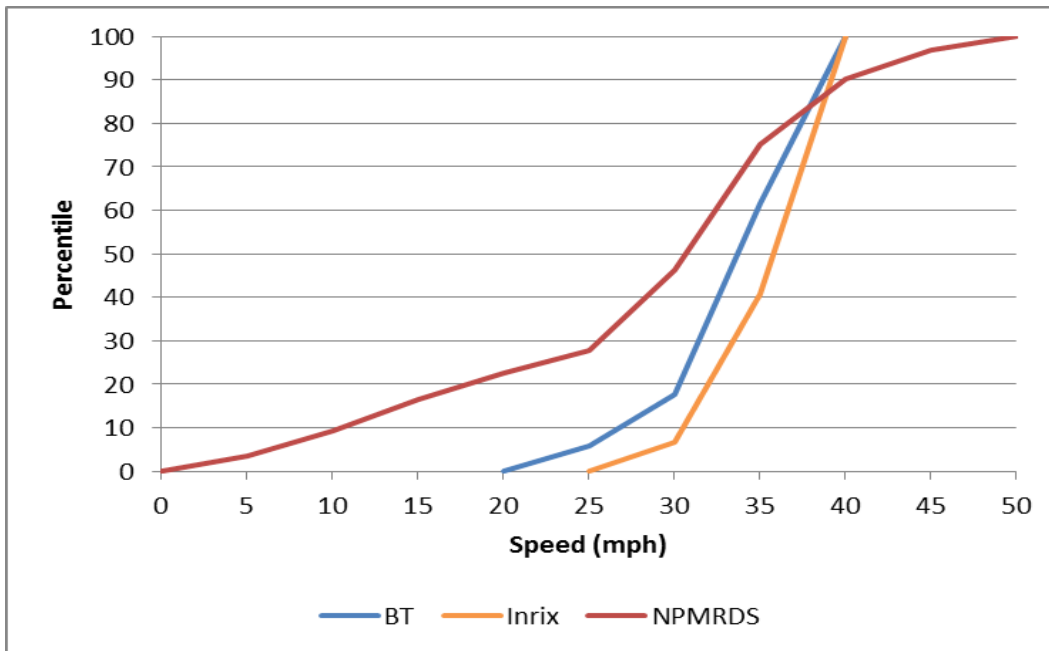


Figure 13. Sample Cumulative Frequency Distribution by Data Source at 8 AM

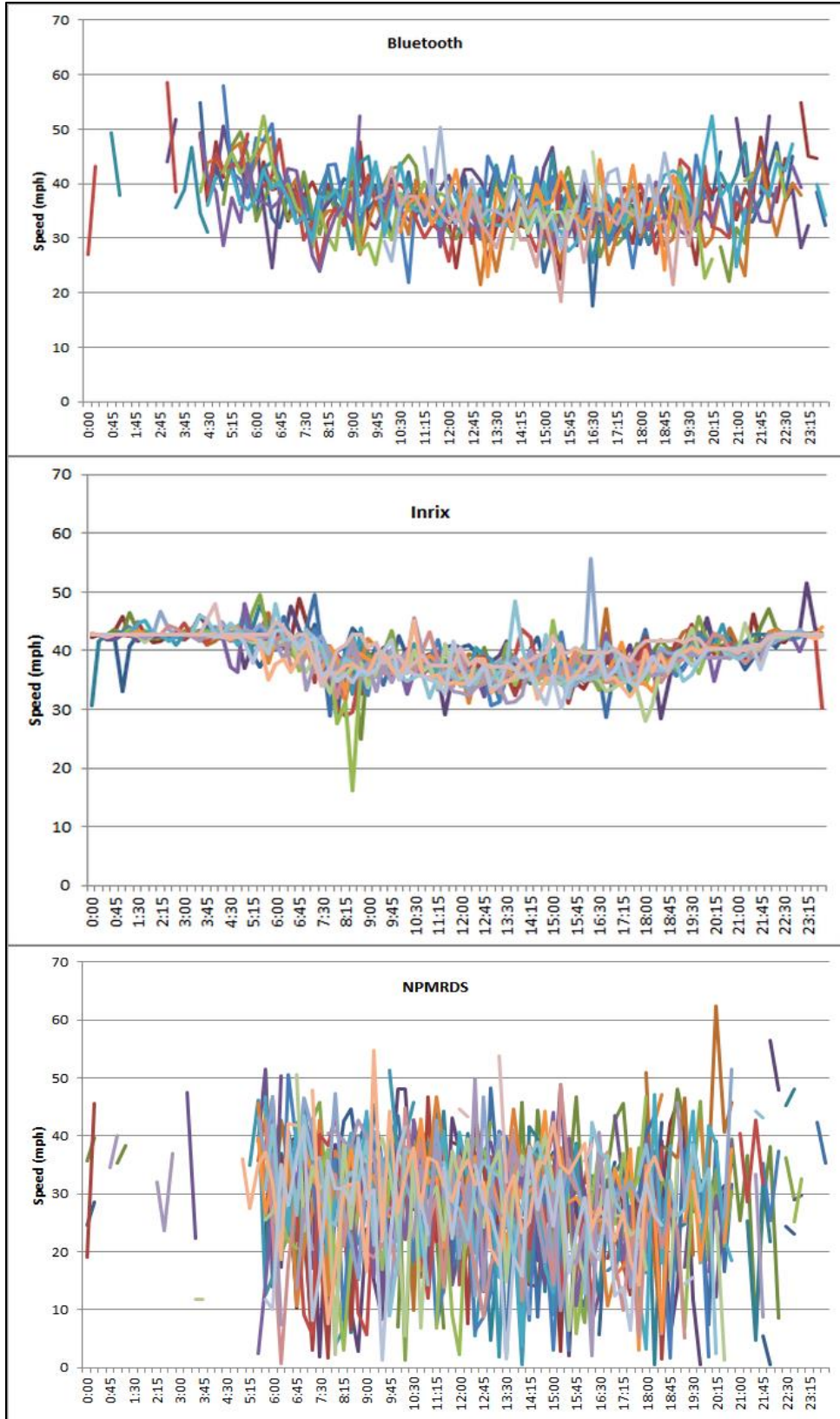


Figure 14. Sample Time-of-Day Speed Patterns by Data Source and Date

Benchmark Analysis

As evident in Table 2 and Figure 15, the Bluetooth, INRIX, and NPMRDS segments did not align perfectly. Their total segment lengths were 15.8, 15.2 (-4.1%), and 15.5 (-1.6%) miles, and their total annual VMTs were 116.7, 108.2 (-7.2%), and 111.2 (-4.7%) million miles, respectively. Since the individual segments from different speed data sources were associated with different volume links, the VMTs were more different across the different speed data source analyses than the network lengths.

Given these differences in network length and VMT, total annual delays were not compared directly. Instead, annual delay per mile was compared across data sources. Since NPMRDS data were available only after July 1, 2013, only data from the second half of 2013 were predominantly used for benchmark analyses. Annual person delay per mile and target delay per mile measures for the entire benchmark network using INRIX data and NPMRDS data are compared to the Bluetooth measures in Table 10, with the reference of daytime LTS. Most of these errors were comparable when PSL was used as the reference speed. Those details are presented later. The order of magnitude of Bluetooth annual delay per mile and target delay per mile were 42,000 and 17,000 hours, respectively.



Figure 15. Major Spatial Attributes of Different Data Sources in Ground Truth Network. TMC = Traffic Message Channel; TMS = traffic monitoring system.

Table 10. Network Delay Errors by Data Source Filtering and Reference Speed

Data Source/Filtering	LTS As Congestion Reference Speed		PSL As Congestion Reference Speed	
	Delay per Mile	Target Delay per Mile	Delay per Mile	Target Delay per Mile
INRIX (unfiltered)	49% lower	81% lower	56% lower	75% lower
INRIX (filtered)	53% lower	83% lower	56% lower	75% lower
NPMRDS (unfiltered)	155% higher	366% higher	125% higher	197% higher
NPMRDS (filtered)	49% higher	111% higher	68% higher	109% higher

LTS = daytime light traffic speed; PSL = posted speed limit.

Although segment-level mean absolute percentage errors between INRIX and Bluetooth were similar to the network delay per mile differences, the NPMRDS segment mean absolute percentage error compared to that of Bluetooth was 195% more using all data and 78% more using filtered data. NPMRDS data quality is definitely a concern with regard to these measures because using different thresholds for filtering will result in very different errors. Further, if these differences for INRIX and NPMRDS delays compared to Bluetooth delays are accurate for larger regions, such differences may be too large for annual performance trend monitoring.

However, the benchmark network in this study was quite small, consisting of only about 15 directional miles on U.S. 17, which is an urban/suburban corridor with observable congestion during the day. For other networks, the differences may be larger or smaller. For example, for the benchmark network, compared to INRIX data, delay per mile was 396% and 190% higher using NPMRDS unfiltered and filtered data, respectively. For the entire network, these values were 752% and 393%, respectively.

Going from 1 year (2013) of data to 6 months (July–December 2013) of data, INRIX annual network delay per mile decreased by 4.3% whereas the Bluetooth measure increased by 2.3%. These movements of a measure in different directions for the same time periods using different data sources are a concern when data with missing records are used. The target delay per mile increased for both data sources, by 0.3% and 8.4%, respectively.

Differences for all other network-level measures, AASHTO RI (both weekdays and all days), TTI, and PTI (for whole day, AM and PM peak periods), are shown in Table 11. Table 11 also uses daytime LTS as a reference. Most errors were 2 to 4 times larger in magnitude when PSL was used as the reference. With Bluetooth data, all RI values were around 1.38; all TTIs were in the range of 1.06 to 1.22; and all PTIs were in the range of 1.16 to 1.37. Weighting factors did not have any consistent pattern of errors for any measure.

Errors for all the noted measures remained similar between unfiltered and filtered INRIX data. RI and PTI had slightly higher errors with the filtered NPMRDS than with the unfiltered NPMRDS, emphasizing the need for more detailed filtering methods for NPMRDS data. On the other hand, INRIX data had a larger magnitude of error for RI than did NPMRDS data, irrespective of filtering. Such error values are possible if the 80th percentile value is close to the benchmark, whereas other values may be far off, as indicated in Figure 13. Therefore, more experience needs to be gained in using both data sets for these measures. TTI using filtered data seems to be the most robust measure.

Table 11. Network Performance Index Errors by Data Source and Filtering

Data Source/ Filtering	LTS As Congestion Reference Speed			PSL As Congestion Reference Speed		
	AASHTO RI	TTI	PTI	AASHTO RI	TTI	PTI
INRIX (both filtered and unfiltered)	12%-14% lower	1.5%-6.5% lower	6%-12% lower	23%-24% lower	12%-18% lower	17%-23% lower
NPMRDS unfiltered	6%-8% higher	13%-20% higher	4%-18% higher	25%-27% higher	35%-44% higher	23%-41% higher
NPMRDS filtered	8%-10% higher	3%-9% higher	5%-16% higher	25%-27% higher	20%-27% higher	22%-35% higher

LTS = daytime light traffic speed; PSL = posted speed limit; AASHTO RI = reliability index as defined by American Association of State Highway and Transportation Officials; TTI = travel time index; PTI = planning time index.

For the benchmark network, annual delay per mile using INRIX data was 8.7% less with filtered data than with unfiltered data. The same comparison for NPMRDS data resulted in a 42% decrease. Delay calculations required only one average speed value per time stamp and day of week. Sufficient INRIX and Bluetooth data existed to calculate these averages for all segments. NPMRDS had gaps in the middle of the nighttime, for which reference speed was used. All other measures were calculated using the available data. Hence 80th percentile values were likely highly affected by missing data. There may be other ways of calculating the 80th percentile value, such as the method used by Rafferty and Hankley (2014), that result in smaller errors in some cases. However, larger errors will result where their assumptions are not appropriate.

Mean percentage errors of all these measures at the segment level were similar to those of the network-level measures in Table 10. AM TTI consistently had errors at the lower end, and PM PTI had errors at the higher end. This observation likely follows from two facts. First, PM VMT is 40% more than AM VMT, even though the time interval is only 20% longer. Second, PTI uses an order statistic (95th percentile value) requiring a large number of data points, whereas TTI uses an average that can be calculated with relatively fewer data points, owing to central tendency. Although TTI is more affected by a few outliers, PTI and RI are more robust. For PTI and RI, only the 80th percentile travel time (corresponding to the 20th percentile speed in Figure 13) needs to be accurate. Over-reporting or under-reporting of other values will not affect the PTI and RI measures.

For individual INRIX and NPMRDS segments, the lengths and VMTs varied from those of the corresponding Bluetooth segment. Each point in Figure 16 represents one segment. Segment lengths and VMTs often did not vary together because the underlying INRIX/NPMRDS TMC-to-TMS link relationships were more detailed than the BT-to-TMS link relationships. Therefore, segment-level measures could not be compared to the benchmark measures in this study. The segment mean absolute percentage errors and mean percentage errors are presented here for a preliminary understanding only. More studies and experience are needed to understand situations when it is appropriate to compare or analyze annual trends for segment-level measures using INRIX or NPMRDS.

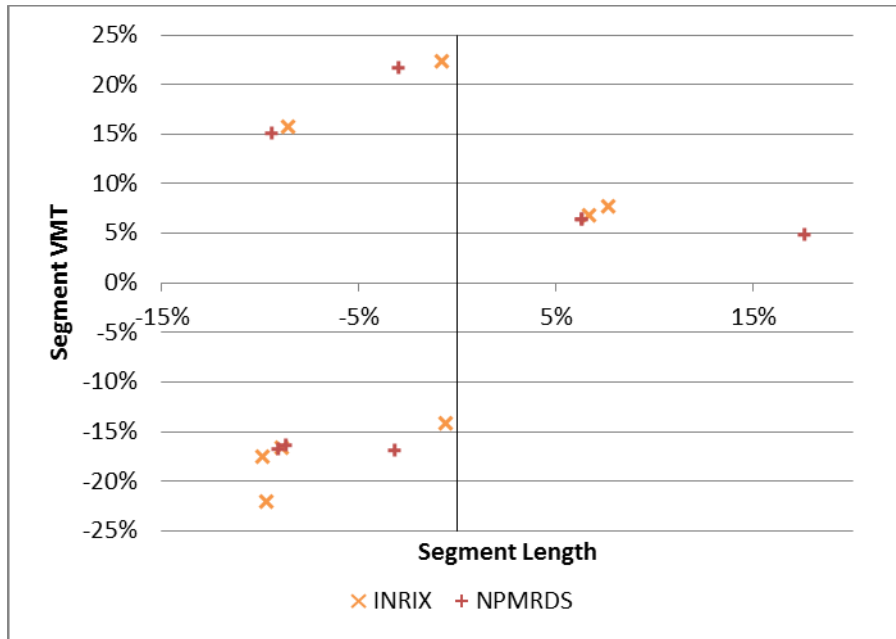


Figure 16. VMT and Length Differences Between Bluetooth and Other Data Sources. VMT = vehicle miles traveled.

Figure 17 shows the correlation of segment-level measures from INRIX data and NPMRDS data with Bluetooth. Although INRIX data typically underestimated all four presented measures, NPMRDS data typically overestimated them. Even though the spread seems visually comparable across the measures, because the magnitudes of delay are quite larger than that of RI80, TTI, and PTI, the percentage differences from Bluetooth for delay are also much larger than those for the other three measures.

Data Quantity and Filtering

Network measures were calculated using INRIX data using a full year of data and just the second half of the year with and without filtering low-quality (confidence score less than 30) data. Missing data resulted in 2% to 4% less delay per mile, whereas filtered data resulted in a 4% to 9% reduction.

Together, missing data and filtering resulted in a 5% to 13% delay reduction. The lower deviations were observed for the entire study network of 288 miles, whereas the higher deviations were observed for the benchmark network of 15 miles. RI values showed around 2% to 3% errors, and most TTI and PTI measures showed less than 1% error for all combinations of missing data, filtering, and network size. These analyses assumed data missing for an entire contiguous period. Randomly missing data, or systematically missing data, say, at low speeds or high speeds, may have different effects on the calculated measures.

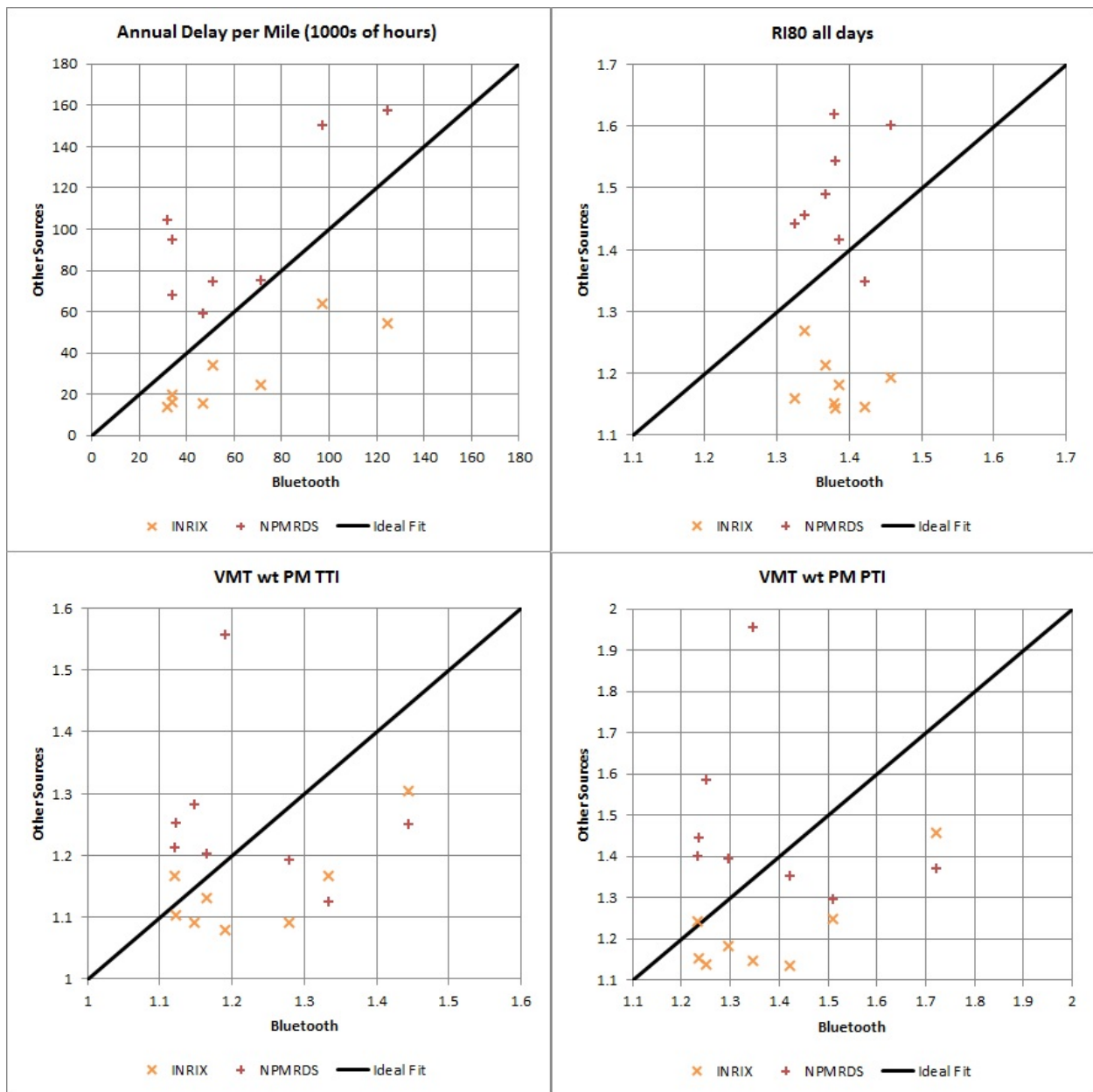


Figure 17. Correlation of Segment Measures Across Data Sources. RI80 = 80th percentile reliability index; VMT = vehicle miles traveled; TTI = travel time index.

Given the low amount of data originally available from NPMRDS, data quantity analysis was not performed. NPMRDS filtering changed delay per mile by 42%, target delay per mile by 50% to 55%, RI by 0% to 2%, PTI by 1% to 7%, and TTI by 9% to 15%. As opposed to INRIX, the lower NPMRDS deviations were mostly observed in the benchmark network and the higher deviations were observed in the entire study network. This observation is a concern because errors did not average out more for larger geographical networks, as expected by information systems such as RITIS VPP Suite. Given the low impact of data filtering on INRIX-based measures and the high impact on NPMRDS-based measures, the remaining analyses used unfiltered INRIX data and filtered NPMRDS data. Given the concerns observed regarding data quantity (mainly for NPMRDS) and errors of measures (for INRIX and NPMRDS), it is not clear

how the remainder of the analyses results will be applicable in the future when the data quantity and quality improve. These results are presented with that caveat and as documentation for future studies to build on the methodology applied here and the findings.

TOD Volume Profiles

Network daily VMTs were less than 0.08% different between the two studied methods, the local CCS method and the UMS method. These minor differences arose because some CCSs are TMS links. At these links, the actual average traffic volumes were used in the local CCS method, whereas published AADT was used in the UMS method. In contrast, differences in AM VMT and PM VMT were about 11% to 13.5% for the INRIX network and 2.4% to 13.4% for the NPMRDS network. These differences arose because of the volume profile differences shown in Figure 18 in which each color represents a unique profile. The 29 unique profiles derived from the 15 CCSs in the study network better illustrate the diversity of traffic compared to the 7 unique UMS profiles. For national or state level measures, these average UMS profiles might hold reasonably well. However, for the 288-mile study network, INRIX delay per mile decreased by almost 11%. At the corridor level, the difference was as high as 17% on Route 105 (2.7 miles long). For the same corridor, eastbound, the difference was 18%. Filtered NPMRDS network delay per mile decreased by almost 2%.

However, these volume profile and VMT differences affected the regional RI, PTI, and TTI by less than 1% for both data sources. If UMS volume profiles are used for calculating delays, small changes from year to year may go unnoticed. However, UMS profiles may be used for calculating RI, PTI, and TTI. During the analysis of this parameter, some CCS links were missing up to 4 months of data. The methodology used to adjust for such missing data and the rationale are presented in Appendix B.

Even for the Bluetooth benchmark network, AM and PM VMTs changed by 5% to 9% and delay by 7.3% between the two volume profile methods.

Definition of “Truck”

Two definitions of “truck” in terms of vehicle classes were examined in this study: Class 5 and above, and Class 6 and above. The network VMT decreased by 0.75% from the first to the second definition. The network delay decreased by 3.2% with INRIX data and by 1% with NPMRDS data for all vehicle speeds. NPMRDS truck speeds were not used because of low data availability. All indices changed by less than 0.5% for both data sets. Actual truck volumes from the CCSs were used to determine the truck hourly volume profiles at the CCS. For TMS links, the same TMS link–CCS association developed in the previous task was used here, in conjunction with the link AADT and the percent trucks of AADT at each link. That approach may not be appropriate if different time or weight restrictions apply to those links. However, the effects of those differences on the network measures are expected to be minor. Which definition of “truck” to use for delay measure depends on other policy implications for VDOT and the MPOs. A consistent definition from one year to the next is necessary to compare trends.

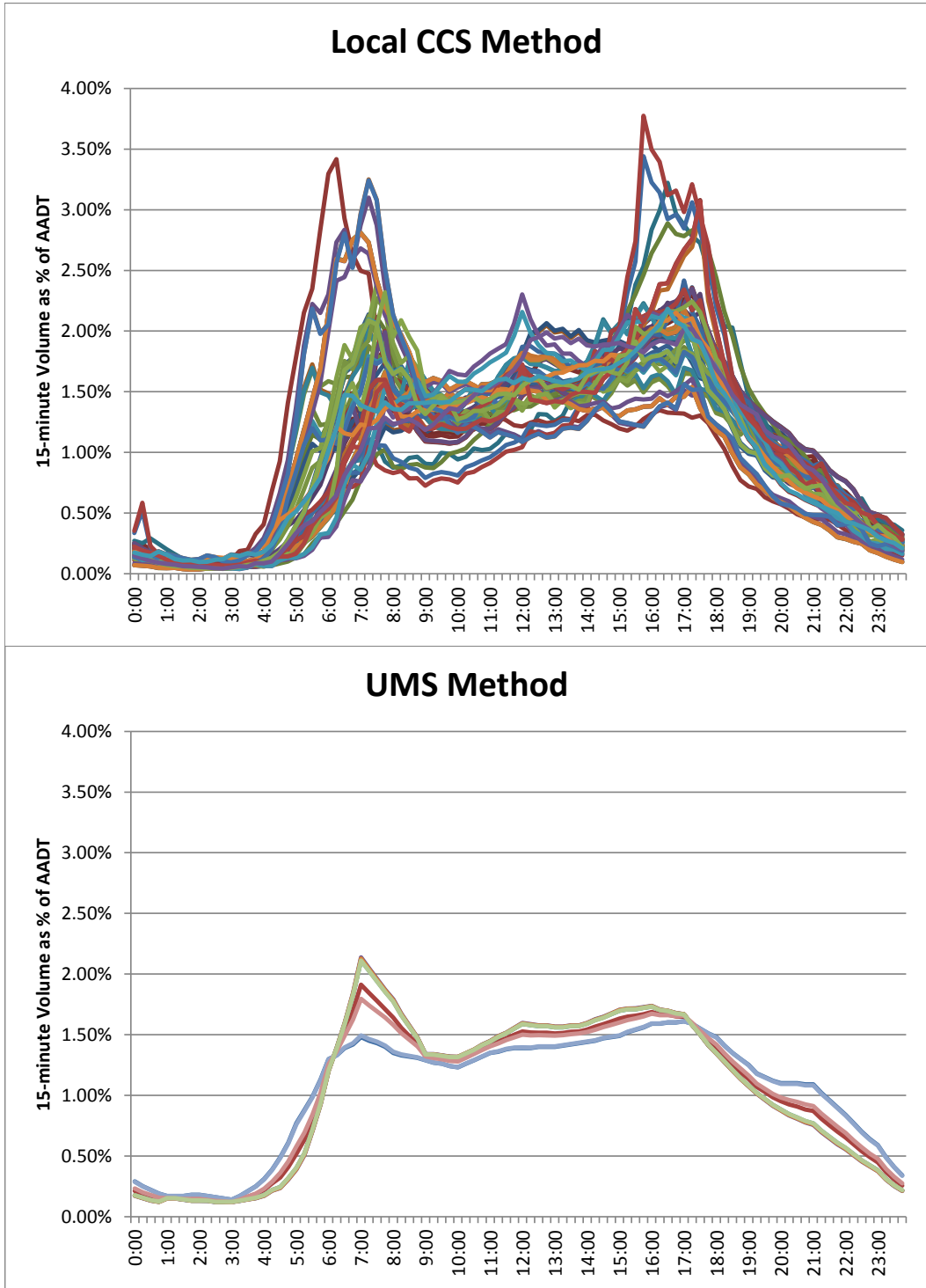


Figure 18. Weekday Traffic Volume Profiles From Different Methods. CCS = continuous count station; AADT = annual average daily traffic; UMS = Urban Mobility Study.

Regional truck VMTs are an order of magnitude smaller than the all-vehicle VMT (the difference is about -95%), irrespective of how “truck” is defined (as Class 5 and above or as Class 6 and above). Delays follow suit at -96.6%. Since these values are so vastly different, it is difficult to identify small variations or trends.

Congestion Reference Speed

Three reference speeds were evaluated in this study: daytime LTS, PSL, and INRIX reference speed. LTS is calculated as the average of the fastest two hourly speeds during the day. The INRIX reference speed is applicable only to INRIX data. The other two are applicable to all data sets. Tables 10 and 11 compare the measure errors from all of these combinations of reference speed, data source, and filtering.

Several results of this investigation are noteworthy. First, filtering had little effect on all INRIX-based measures but NPMRDS delay and TTI measures were affected noticeably. This again shows the high variability in NPMRDS data and the need for filtering compared to INRIX data. Second, with filtered data, the magnitude of error for almost all measures increased when PSL was used as the reference speed compared to LTS for both data sets. Delay error magnitudes increased by 50% to 150%, target delay magnitudes decreased slightly, and all index errors increased by 2 to 4 times. Further, all the measures based on the INRIX reference speed from INRIX data were similar to those of PSL-based measures. Going from LTS to the INRIX reference speed increased network delay by 51%, TTI and PTI by 2.4% to 5%, and RI80 by 3% to 4%. It should be noted that the Bluetooth measures themselves changed when the reference speed was changed from LTS to PSL. Delay increased by 125%, target delay by 300%, and all indices by 22% to 28%.

Congestion Threshold

For this analysis, daytime LTS was used as the reference. As expected, as the congestion threshold increased, the number of segments and hence congested miles increased (Table 12). However, the VMT-weighted congestion hours did not increase monotonically with the threshold. When the number of segments increased, even as the congestion hours in the previously congested segment remained the same, if newer segments with congestion were affected for fewer hours, the weighted network congestion hours decreased in some cases. Therefore, network congestion hours should not be monitored and targeted as a performance measure independent the spatial extent (miles) of congestion. A multiplication of these two factors is presented here in hours-miles as one approach to address this situation. Once again, the large number of NPMRDS segments affected by congestion (190 of 213) points to the large number of low speed values.

If delays are calculated using a congestion threshold, depending on which threshold is used, different segments will be identified as delayed or not. In addition, the intensity of delay will also depend on the selected threshold. If VDOT uses a uniform threshold for the entire state, individual regions, districts, and MPOs have to adjust their policies to reflect what level of delays and congestion they target to mitigate. Alternately, each MPO, district, or region may define their own thresholds. The main advantage of the former approach is standard definition.

The main advantage of the latter approach is that some regions gain the flexibility to build locally acceptable levels of expected and tolerable congestion or delay into the definition (and hence their budgeting processes, thereby facilitating easier communication with elected officials and the public). This flexibility may be desired because of inherent differences in rural and urban regions.

Table 12. Effect of Congestion Threshold on Congested Hours and Miles

Data Source	Threshold	Congested Hours			Congested Miles			Total Congestion (Hours-Miles)			No. of Segments
		AM	PM	All Day	AM	PM	All Day	AM	PM	All Day	
INRIX	0.6		3.3			1			3.1		1
	0.7		3			1.6			4.7		3
	0.8		3	5.8		10.2	2.6		30.1	15.3	12
	0.9	2.4	3.7	8.1	14.8	60.5	38.7	35.8	225.1	312.8	53
NPMRDS	0.6		2.9	5.1		7.9	1	0.0	23.2	5.2	12
	0.7	2.3	2.9	6.1	0.6	24.3	11.3	1.3	71.0	69.3	28
	0.8	2.4	3.2	7	42.4	108.2	111	101.9	345.2	777.6	108
	0.9	2.8	4.2	11	191	233.9	243.1	530.5	976.0	2663.9	190

Peak Period Definition

By design, this definition affects only peak period VMT, PTI, and TTI values. When the peak period hours were reduced, even as the peak period VMTs decreased by 27% in the AM and 32% in the PM, both PTI and TTI changed less than 1.5% using INRIX data and less than 2.7% using NPMRDS data. This robustness is a useful result: VDOT could potentially apply one peak period definition for the entire state and also not change it from one year to the next. However, one potential downside of the robustness of the measures is the lack of sensitivity to geometric and operational projects implemented by VDOT. Further, the study network results may not be representative of highly congested areas such as VDOT’s Northern Virginia District, and VDOT and MPOs need to gain more experience with data and measures before making such a decision to implement a uniform peak period definition for the entire state. Finally, peak period definitions depend on traffic volumes as well as speeds, and local traffic experts should weigh in on the appropriate peak period definitions so that the performance measures are meaningful and useful in local decision making. Even small changes on the order of 1.5% to 3% are likely important at a corridor level to monitor and manage.

Time Aggregation

Hourly aggregation of speeds had minimal impacts on INRIX-based network measures (less than 0.8%) compared to 15-minute aggregation. Some PTI measures varied up to 0.5%; however, most PTIs, TTIs, and RIs varied less than 0.1%.

Hourly aggregation decreased NPMRDS-based network delay by 12.4%. This result is likely due to the large number of low speeds observed in this data set that were offset more by hourly aggregation than 15-minute aggregation. All indices differed by 0.5% to 4%.

Segmentation

Results from analyzing the entire study network with the three INRIX segmentation approaches (TMCs, custom segments, and entire corridor-direction) and two NPMRDS segmentation approaches (TMCs and entire corridor-direction) are presented in Table 13. The percentage differences are shown with respect to the respective TMC segmentation. Given the low quantity and quality observations for NPMRDS, the fact that short internal TMCs were not part of the NPMRDS network, the time requirements for conflation of custom segments to traffic volume links, and the low variance in the measures using INRIX data, custom segmentation was not carried out for NPMRDS.

Custom segmentation and base TMC network measures were comparable. As expected, very long segments produced noticeable delay reduction as congestion in some locations was washed out by free flow in other locations. Therefore, very long segments are not deemed appropriate. INRIX RI, TTI, and PTI for long segments were affected much less than were NPMRDS measures.

One downside of using the base TMCs as provided by the vendor is that they can change in length and quantity over time whereby direct segment-to-segment comparison across years will not be possible. For network measures, treating each TMC as a segment will greatly reduce the work load and the subjectivity potentially introduced in creating custom segments.

Table 13. Effect of Segmentation on Regional Measures

Measure	INRIX		NPMRDS
	Custom Segments	Each Corridor-Direction As a Segment	Corridor-Direction
Delay	-3.4%	-29%	-43%
RI	Less than -1.9%	-1.5% to -4.9%	-2.4% to -5.7%
TTI	Less than -0.7%	-0.1 % to -2.7%	-5.4% to -9.5%
PTI	Less than -1.3%	-1.1% to -2.3%	-3.7% to -8.8%

RI = Reliability Index; TTI = Travel Time Index; PTI = Planning Time Index.

Weighting Factors and Correlation Among Measures

Across all the parameters, calculation options, spatial aggregation, and time periods studied, the four weighting factors produced highly correlated RI, PTI, and TTI measures. The different options often produced changes less than 2% across the different weighting factors.

Network truck VMTs and INRIX-based delays were 95.5% and 96.6%, respectively, lower than that of all vehicles. Unit- and length-weighted RI80, PTI, and TTI measures were the same for all vehicles and trucks, since volume was not included. Even VMT- and volume-weighted RI80, PTI, and TTI network measures differed by less than 2.8%, 2.2%, and 2.6%, respectively, between all vehicles and trucks.

All three index measures, irrespective of the weights, spatial resolution, time periods, data sources, and parameter options, were highly positively correlated. The following detailed results are presented for INRIX-based measures, which are comparable to NPMRDS-based measures. In the AM and PM peaks, PTI and TTI correlation coefficients were always above 0.85, irrespective of the spatial resolution (corridor, corridor-direction, or segments) and

weighting factor. Of the daily reliability measures pairs (PTI, TTI, and RI80 all days and RI weekdays), 99% had correlation coefficients greater than 0.85 at the segment level, 93% at the corridor-direction level, and 98% at the corridor level. Across the parameters, at the regional level, daily and PM reliability measure pairs always had correlation coefficients greater than 0.85. Only 71% of the AM PTI and TTI pairs had correlation coefficients greater than 0.85. Volume- and unit-weighted AM TTI had the lowest correlations with all the PTI measures. All the other AM measures pairs had a correlation above 0.85. One potential reason for these results is that the study network had lower demand and congestion in the AM peak compared to the PM peak.

Cambridge Systematics, Inc., et al. (2013) stated that in data poor situations when a sufficient quantity of data is not available to calculate all the measures, some measures (such as PTI) can be estimated from others (such as TTI). The high correlation among the different measures in this study supports such an approach. Given the correlations among measures can be low under some congestion regimes in other locations, VDOT should calculate all these measures in the near future.

However, the high correlation of the network measures among all four weighting factors studied is also concerning because from one year to another, as the network, demand, and operational strategies change, the network index measures may not be sensitive to such agency actions. VDOT needs to gain more experience in this area.

Geometric and Traffic Factors

At the segment, corridor-direction, and corridor levels, all measures were plotted against the geometric and traffic factors: AADT, length, signal density, and PSL. No visible patterns or clear relationships emerged between the measures and the factors. The highest R-squared value was observed between delay per mile and signal density, at 0.5. All other R-squared values were less than 0.25, or even 0.1.

Task 4 Results: Recommendations for Calculating Performance Measures

An objective of this study was to develop prescriptive recommendations on calculating arterial system performance measures. However, low data availability and the numerous parameter options constrained the study to develop considerations instead, as listed in this section. There is often no one simple answer for the applicability of options to a certain geographic area, time period of analysis, or purpose of measurement. At a minimum, in the selection of appropriate calculation parameter options, the tradeoffs across the following should be considered: (1) robustness of measures with regard to data quality and variability; (2) desired level of sensitivity and precision of performance measures to agency actions; (3) purpose of the measure; and (4) analysis resources available (data availability and granularity, data storage, computational servers, staff).

Considerations for Calculating Arterial System Performance Measures

The following considerations are drawn from a limited network and past data. The case study network consisted of 288 directional miles of urban/suburban/rural arterials, with nearly 500 signalized intersections; the benchmark network consisted of 15 directional miles. Therefore, some considerations may not apply fully to a different network, such as one with heavy congestion as in Northern Virginia. Transportation experts and probe data vendors alike expect data quality, availability, and coverage to keep improving over time, thus providing a more solid base for these performance measures.

- *Volume profiles.* Compared to local CCS traffic volume profiles, UMS profiles decreased INRIX-based study network delays by 11% and NPMRDS-based delay by 2%. Network index measures were less than 1% different for both data sources. Although daily VMTs remained comparable between the two approaches across the different spatial levels of analyses (<0.08% difference), PM VMT was about -11% to -15% different. As expected, local traffic profiles had more diversity than UMS profiles.
- *Definition of “truck.”* Network VMT for vehicles Class 6 and above was 0.75% less than that for vehicles Class 5 and above; INRIX-based delay was 3.2% less, and NPMRDS-based delay was 1% less. All index measures changed less than 0.5%.
- *Congestion reference speed.* Compared to daytime LTS (average speed of the least congested 2 hours during the day), using the INRIX reference speed as the FFS resulted in a regional delay increase of 51%. The index measures increased by 3.4% to 5.1%. All measure values calculated using the INRIX reference speed and PSL were comparable.
- *Congestion threshold.* As the congestion threshold increased, congested road miles increased in a monotonic, non-linear manner. However, VMT-weighted network congested hours did not vary monotonically, since newly congested segments with fewer hours and higher VMT can reduce the network congested hours.
- *Peak period definition.* Reducing each peak period by 2 hours impacted PTI and TTI by less than 1.5% using INRIX data and less than 2.7% using NPMRDS data.
- *Time aggregation.* Compared to 15-minute aggregated data, 1-hour aggregated data impacted INRIX-based measures by less than 0.8%, NPMRDS-based network delay by 12.4%, and NPMRDS-based index measures by less than 4%.
- *Spatial segmentation.* Compared to INRIX TMC segments, custom segments based on basic rules of thumb (such as homogeneous traffic volume, speed limit, number of lanes, signal density, etc.) decreased network delay by -3.4% and all index measures by 0.7% to 1.9%. However, considering very long segments, such as the entire corridor in each direction, noticeably washed out congestion and decreased the delay

by 29% and index measures by 2.3% to 4.9%. The corresponding reductions using NPMRDS data were 43% for delay and 5.7% to 9.5% for index measures.

- *Weighting factors.* Contrary to expectations, the various index measures across different parameter options had less than a 2% difference when calculated using different weighting factors. The main concern with this is that the network index measure may not be very sensitive to VDOT operational or traffic engineering actions at individual segments. As such, many agency actions may go unnoticed.
- *Geometric and traffic factors.* System performance measures depend on traffic demand and road capacity supply. No noticeable patterns were observed between the studied measures and individual geometric and traffic factors such as AADT, length, signal density, and PSL. The highest R-squared value was observed between delay per mile and signal density, at 0.5. All other R-squared values were less than 0.25, or even 0.1.
- *Combined monitoring of measures.* A single measure (e.g., congested miles) explains only one aspect of congestion. Monitoring multiple measures simultaneously (congested miles and congested hours) provides a more robust picture. As the congestion threshold increased, congested road miles increased in a monotonic, non-linear manner. However, VMT-weighted network congested hours did not vary monotonically, since newly congested segments with fewer hours and higher VMT can reduce network congested hours. Since congested miles and hours in a network explain different dimensions of congestion, VDOT should monitor them together.

Additional Considerations

Weighting Factor

In principle, if trucks are assumed to travel during the same time as cars and their proportions are similar on different roads, reliability measures for cars and trucks are expected to be similar and length weight is reasonable. If trucks are restricted in some locations, using length weights after ignoring those road segments is more reasonable. If trucks travel at different times than cars or in different proportions on different road segments, using volume and VMT weights is more reasonable for differentiating system performance for cars and trucks.

INRIX provides only one speed data stream and considers the difference between cars and trucks to be insignificant. This is reasonable for congested traffic regimes, geometries where passing is not allowed, or flat terrain where truck speeds are impacted minimally. However, the differences will be significant on steep terrains and where trucks are restricted (whether by weight, speed, class, or time of day); this was not evaluated in this study but is important to note for other locations. The former can be observed only if separate data streams are collected for cars and trucks. The latter can be observed in the traffic volumes served by the road segment. As an extension, network truck traffic performance can be implicitly monitored using the truck traffic demand served, even if similar speeds are assumed for cars and trucks. When delays and bottlenecks are inherently different between cars and trucks on a network, differences in RI, PTI,

and TTI would be expected. Using truck volume or VMT as a weighting factor is expected to illuminate these differences better, in principle, even if not in calculated numbers.

Data Quality and Quantity

VDOT already uses segment-level measures for Smart Scale evaluations and other analyses, such as before-after studies. However, network-level measures and annual monitoring are still relatively new concepts, especially for arterial systems. Considering the noticeable impacts of speed data quality and quantity on the network measures observed in this study, VDOT needs to gain more experience in this area. Further, during this time period of gaining experience, VDOT needs to request that FHWA not apply penalties or tie appropriations to target achievement.

VDOT recently contracted with INRIX to procure XD data, transitioning from the TMC data used in this study. The network coverage increased with this transition, which should improve VDOT's ability for internal system performance monitoring. However, both the TMC and XD networks are supposed to cover the entire NHS, which is required for MAP-21 reporting. In fact, the two networks package the same underlying probe data to different resolutions. In a presentation to VDOT, a representative of INRIX also mentioned improvements in data quality owing to shorter link lengths (R. Schuman, unpublished data, 2015). Although these shorter links are useful for showing detailed real-time speeds on maps, for accurate queue length measurements and a more narrow isolation of problem segments, the researcher does not expect them to affect network annual delay, RI80, TTI, or PTI by a large amount. As mentioned by Hallenbeck et al. (2015), the researcher, too, expects the overall probe data quality for the TMC and XD networks to improve over time and hence improve the value and accuracy of the performance measures.

Based on error values studied for the benchmark network, TTI is the most robust measure (i.e., the least affected by data quality issues) and the most similar across data sources (1.5% to 9% deviation). The AASHTO RI and PTI are comparable in robustness but less similar across data sources, with a deviation of 5% to 16%. Delay deviations were about 50% for both INRIX and NPMRDS data. However, it is noted that if TTI, RI, and PTI are robust to large variations in data, their sensitivity to VDOT actions may also be low. A detailed understanding of these issues is necessary before stringent target setting and data-based performance management approaches are applied.

Congestion Reference Speed

There are advantages and challenges to using any of these three reference speeds: vendor-supplied reference speed, PSL, and daytime LTS. Vendor-supplied reference speeds can change over time, but the reasons for the changes are not documented. Some vendors, such as NPMRDS, do not provide reference speeds. PSL is available for state-maintained roads but not for city- or county-maintained roads. PSL and LTS are comparable for freeways and are desirable references to capture all delays. However, by design, PSL is not achievable when traffic control devices are present. Therefore, if PSL is used as the reference, appropriate “acceptable congestion/delays” also must be developed and communicated to citizens and

elected officials. LTS-based delay will be artificially low for severely congested roads, whether because of heavy traffic volume or inefficient signal timings.

For any one homogeneous segment, the congestion reference speed does not make much difference because it is just a reference line drawn to calculate delay and other measures. Only the magnitude of the measure will be affected. Depending on the use of the measure, such magnitude differences may be unimportant (such as for annual trend monitoring) or easily accounted for (such as prioritizing two similar segments for projects). However, network measures will be impacted in complex ways by the reference speed selected. Selecting PSL may show a downtown street to be much more congested than a suburban roadway. Selecting daytime LTS may show the opposite.

For all these reasons, VDOT should use both PSL and LTS in the near future to gain further experience.

Resources to Calculate Measures

Even for the small study network of 288 directional miles, calculating measures with some parameter options took about 4 hours to run completely on a standard issue VDOT laptop (with 6 GB RAM, Intel Core i5-2520M 2.50 Hz processor, 64-bit Windows 7 operating system). Calculating these measures for the entire state of Virginia, even with optimized data flow, using personal computers and SAS will take several days. Rafferty and Hankley (2014) also mentioned that relational databases and scripting are essential to analyze NPMRDS data as is an understanding of performance or hardware limitations. Therefore, optimized databases, dedicated servers and/or service, and experienced staff resources are necessary to analyze statewide data in a reasonable timeframe of not more than a few hours.

Cambridge Systematics, Inc. (2016) prepared a white paper on the step-by-step calculation procedures for the proposed measures in the NPRM. With regard to the data analysis needs highlighted, the authors stated: “Calculating the performance measures in the proposed Part 490 would require more than a spreadsheet on a basic desktop computer. Instead, more powerful computer software and hardware would be needed, as well as a technical analyst with intermediate skills in data management, integration, and summary.” The authors further documented specific requirements such as “capability for routinely storing and processing at least 5 to 10 terabytes of data” and “ideally, a server (with appropriate disk redundancy and system backup) dedicated to storing and processing very large data sets.” Further, Pack and Lund (2014) estimated that the emerging connected and automated vehicle paradigm will increase traffic data availability and analytical needs by an order of magnitude beyond the probe data currently available. In recent years, international conferences such as the Transportation Research Board’s 2016 Annual Meeting and NATMEC 2016 have been focusing on storage and analytical solutions to this emerging data explosion, through the “big data” approach. Although not investigated as a part of this study, big data approaches seem promising and even essential (Cambridge Systematics, Inc., 2016; Pack and Lund, 2014) for calculating statewide system performance measures and for actively managing the system (through what-if analyses and identification of the root causes of problems).

CONCLUSIONS

- *Data availability should be sufficient for daytime analyses of the studied measures.* For the three data sources, daytime (5 AM-10 PM) availability of filtered data was about 15% higher than for the whole day (34%-60%). Therefore, all these data sets are more suitable for analyzing recurring traffic congestion during daytime, rather than nighttime, work zones or special events.
- *Bluetooth and INRIX data exhibited comparable day-to-day variability, whereas NPMRDS data exhibited a much higher variability than either (with the 2013 data studied).* NPMRDS TMCs investigated in this study exhibited much larger variations in the raw data and the measures compared to Bluetooth links and INRIX TMCs, even as the average speed profiles were comparable. Raw data were analyzed through visual assessments of daily speed profiles, CFDs, and standard deviations by time of day. Further, data filtering changed NPMRDS network delays by more than 40%, which is practically very high for annual system performance monitoring, target setting, and management. Significant improvements in NPMRDS data availability and quality are needed before NPMRDS data are used for network delay performance monitoring.
- *Large amounts of missing data result in significant impacts to system performance measures.* Six months of missing data caused INRIX delay per mile for the benchmark network to decrease by 4.3%, although the same measure with Bluetooth data increased by 2.3%. Even though detailed and exact studies on the effect of missing data on measures could not be carried out, the presented observation emphasizes the need for attention in interpreting measures when large portions of data are missing.
- *Some performance measures could be reliably estimated from other measures.* This observation is especially useful if data quality or availability is not sufficient to calculate a specific measure directly. All index measures for each data source, irrespective of the weights, spatial resolution, time periods, and parameter options studied, were highly positively correlated. Most R-squared values were above 0.85. Most low correlations were for the AM peak periods, which had lower congestion.

RECOMMENDATIONS

1. *The Virginia Transportation Research Council (VTRC) should use the detailed findings in this study to support VDOT's TED and OD in developing comments on the NPRM with regard to system performance measures.* This recommendation was carried out as a technical assistance (TA) project. The results and a draft form of this report were provided to VDOT's TED and OD.
2. *VDOT's TED and OD should calculate and monitor trends in the arterial performance measures examined in this study using the considerations developed in this study for a sample set of corridor segments.* This approach will help VDOT gain experience with,

become familiar with, and identify improvements in data quantity and quality in a timely manner so as to use the measures appropriately.

3. *VDOT's TED and OD should continue to support periodic evaluations of probe-based speed data and network measures (INRIX, NPMRDS, and other vendor data sets of interest) using ground truth data.* These exercises will help VDOT understand when the quality of the data improves to sufficient levels for use of the data in more precise target setting. Although evaluation studies conducted so far (e.g., the I-95 Corridor Coalition Vehicle Probe Project [Young et al., 2015] and VDOT internal studies) indicated a higher data quality in rural areas and on roads with low signal density and high AADT, no studies have looked at the cumulative effects of the data quality on the network measures that include all the roads in the area. Potential research avenues include the ongoing VPP evaluations currently being carried out by the I-95 Corridor Coalition; permanent benchmark data collected from some arterials in Virginia; VTRC TA studies; and pooled fund studies with other states.
4. *VDOT's TED and OD should work with VDOT's Information Technology Division to study and mobilize necessary data storage and computational servers for calculating statewide system performance measures.* These resources are necessary in order to calculate performance measures for the entire state in a reasonable timeframe and to carry out additional sensitivity analyses.

BENEFITS AND IMPLEMENTATION

Benefits

The primary benefits for VDOT from implementing these recommendations are improved preparedness and compliance with the federal rulemaking, MAP-21, and the FAST Act. Implementation of Recommendations 2, 3, and 4 will help VDOT make the best use of the resources in procuring and analyzing traffic data in an efficient and effective manner to monitor arterial system performance and ultimately manage the arterial systems.

Implementation

With regard to Recommendation 1, VTRC staff used the findings of this study to support VDOT's TED and OD to develop prompt and appropriate comments on the NPRM as part of the TA project "VDOT Travel Time Research Program." The comment period ended August 20, 2016, and VDOT provided comments in a timely manner.

With regard to Recommendation 2, as part of the same TA project, in FY17 and FY18 VTRC will develop tools, a schedule, and a format for calculating performance measures and monitoring trends in the measures and the data quality. VTRC will share the tools and results of that exercise with VDOT's TED and OD and set up an ongoing monitoring program in cooperation with TED and OD. This effort will include roadways with diverse characteristics, including rural, urban, and suburban routes. These tools will be developed by June 2018.

With regard to Recommendation 3, the TA project is already scoped for VTRC to carry out limited data validation and performance measure assessments. These validations will be performed on a periodic, ongoing basis, as determined together by VTRC and VDOT's TED and OD. The I-95 Corridor Coalition VPP studies also carry out data validation studies across various corridors in the member states. Both of these projects have been set up on a continuing schedule to perform spot studies as needed.

With regard to Recommendation 4, VDOT's TED and OD will work with VDOT's Information Technology Division to identify data storage and computational server needs and study big data approaches to resolving those needs. These tasks will be carried out in FY17 and FY18 in time to calculate and report system performance measures to the U.S. DOT for MAP-21 compliance. The exact time for completing this task depends on the Final Rule published by FHWA. Meanwhile, VTRC has started supporting VDOT's TED and OD in assessing big data analysis approaches for performance monitoring purposes.

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APPENDIX A

DETAILED CALCULATION METHODOLOGIES FROM SELECT LITERATURE

Methodology for Determining Traffic Volume Profiles Used in the 2015 Urban Mobility Scorecard

This methodology was used by the Texas A&M Transportation Institute's *Annual Urban Mobility Scorecard* (Schrank et al., 2015) to determine traffic volume profiles. Sixteen national average traffic distribution profiles are available from the literature. One of these profiles is applied to each TMC (or other probe data link), along with HPMS AADT, to calculate hourly traffic flow based on the following factors:

- First, each TMC is assigned a functional class (as freeway, for access controlled highways, and non-freeway, for other major roads).
- Second, a day type is determined (as weekday, for Monday through Friday, and weekend, for Saturday and Sunday). To calculate total traffic volume for each day of the week, the following fractions of AADT are assigned:

Monday-Thursday: 1.05

Friday: 1.10

Saturday: 0.90

Sunday: 0.80.

- Third, traffic congestion level is determined. A peak period speed reduction factor is calculated as follows:
 1. Calculate a simple average peak period speed (for morning and evening weekday peak periods together) for each TMC.
 2. Calculate FFS from nighttime hours (10 PM-5 AM).
 3. Calculate the speed reduction factor (SRF) as the ratio of average peak period speed to FFS.
 4. Assign congestion level based on SRF and functional class from Table A1.

Table A1. Relationship of Congestion Level to SRF and Functional Class

Congestion Level	Freeways	Non-freeways
No to low congestion	90%-100%	80%-100%
Moderate congestion	75%-90%	65%-80%
Severe congestion	<75%	<65%

- Fourth, assign directionality to the TMC based on the difference in average speeds in the AM and PM peak periods. If the difference is less than 6 mph, assign even volume distribution.

The Texas A&M Transportation Institute is also developing truck-specific traffic volume profiles, but these profiles were not used in this study given they have yet not been and used in any published studies.

AASHTO SCOPM Methodology for Calculating Delays and Reliability Indices

In the AASHTO SCOPM report (AASHTO, 2012), the methodologies for calculating annual hours of delay and annual hours of truck delay are similar. The methodology for calculating annual hours of truck delay is as follows:

1. Establish corridor segments.
2. For each corridor segment, determine the agency-specified threshold speed.
3. For each day and corridor segment, calculate the daily hours of truck delay:

$$\text{Daily hours of truck delay} = \frac{\text{Freight VMT}}{\text{Travel speed}} - \frac{\text{Freight VMT}}{\text{Threshold speed}}$$

4. Sum the daily hours of truck delay for each day to obtain the weekly delay per segment.
5. Multiply the weekly hours of delay per segment by 52 to obtain annual delay per segment.
6. Sum all annual delays per segment to obtain the annual hours of truck delay.

The procedure for calculating the freight reliability index (RI) is presented here and is similar to the procedure for calculating the overall traffic RI:

1. Establish corridor segments, and repeat Steps 2 through 6 for each.
2. Determine the agency-specified threshold speed for corridor segment, and calculate agency travel time.
3. Calculate the travel time for each time interval for each day of the calendar year (365 days).
4. For each time interval, array the travel time.
 - From these 365 calendar days, travel times are arranged in ascending order.
 - From this list, the 80th percent worst travel time is selected. This will be the annual average 80th percentile travel time for that 5-minute interval, across all days.

- Repeat the same process for the other 287 5-minute intervals.
5. From Step 4, array the 288 annual average 80th percentile travel time values.
 - Arrange them in ascending order.
 - From the list, select the 80th percent worst travel time. This will be the 80th percentile travel time.
 6. Calculate the freight RI as:

$$\text{Freight } RI_{80} = \frac{\text{80th percentile travel time}}{\text{Agency travel time}}$$

7. To calculate the statewide average RI value, weight the individual corridor RI values by truck miles traveled in each corridor.

The methodology further suggests using either the 240 work days or all 365 days of the year in Steps 3 and 4. In this study, since 15-minute and 1-hour intervals were used instead of 5-minute intervals, the number of time periods was 96 and 24, respectively.

Turner and Qu Methodology for Calculating Arterial Delays and Reliability Indices

Two definitions of *congestion* are provided by Turner and Qu (2013):

- *Congestion*: travel time or delay in excess of that normally incurred under light or free flow travel conditions.
- *Unacceptable congestion*: travel time or delay in excess of an agreed-upon norm [or target value]. The agreed-upon norm may vary by type of transportation facility, geographic location, and time of day.

Tables A2 and A3 contain the calculations for delay and RIs. Target values were assigned as shown in Table A4 to factor in land use.

Table A2. Annual Delay and Target Delay Calculation

Hour	Length (a)	Intersection Density (numbers per mile)	Target Value ¹ (b)	Average Speed (mph) (c)	Light Traffic Daytime Speed ² (mph) (d)	Target Speed ³ (mph) (e) =(b) * (d)	Travel Time Difference ⁴ (f) = $Max(\frac{1}{(c)} - \frac{1}{(d)}, 0)$	Hourly VMT (Vehicle Miles) (g)	Hourly Delay (h) =(f) * (g)	Target Travel Time Difference ⁵ (i) = $Max(\frac{1}{(c)} - \frac{1}{(e)}, 0)$	Hourly Target Delay (j) =(i)*(g)	Annual Person Delay Per Mile (k) = $\frac{(h)*1.25*52}{(a)}$	Annual Target Delay Per Mile (l) = $\frac{(j)*1.25*52}{(a)}$
0	2.73	17	0.75	30	29	29*0.75=21	Max(1/30-1/29, 0) = 0	1,464	0 * 1464 = 0	Max(1/30-1/21, 0) = 0	0 * 1464 = 0	0 * 1.25 * 52 / 2.73 = 0	0 * 1.25 * 52 / 2.73 = 0
1	2.73	17	0.75	30	29	21	0	896	0	0	0	0	0
2	2.73	17	0.75	30	29	21	0	617	0	0	0	0	0
3	2.73	17	0.75	30	29	21	0	579	0	0	0	0	0
4	2.73	17	0.75	30	29	21	0	952	0	0	0	0	0
5	2.73	17	0.75	28	29	21	0.000769299	2,425	2	0	0	44	0
6	2.73	17	0.75	27	29	21	0.00237461	5,788	14	0	0	328	0
7	2.73	17	0.75	25	29	21	0.004502127	8,617	39	0	0	925	0
8	2.73	17	0.75	26	29	21	0.004132297	8,679	36	0	0	855	0
9	2.73	17	0.75	24	29	21	0.005880295	8,956	53	0	0	1256	0
10	2.73	17	0.75	24	29	21	0.006901694	10,221	71	0	0	1682	0
11	2.73	17	0.75	24	29	21	0.007493086	11,775	88	0	0	2104	0
12	2.73	17	0.75	24	29	21	0.006719416	12,403	83	0	0	1987	0
13	2.73	17	0.75	25	29	21	0.005750436	12,422	71	0	0	1703	0
14	2.73	17	0.75	24	29	21	0.006839649	13,829	95	0	0	2255	0
15	2.73	17	0.75	23	29	21	0.008039923	16,369	132	0	0	3138	0
16	2.73	17	0.75	23	29	21	0.008064418	17,989	145	0	0	3459	0
17	2.73	17	0.75	24	29	21	0.006322855	15,670	99	0	0	2362	0
18	2.73	17	0.75	28	29	21	0.000629813	10,887	7	0	0	163	0
19	2.73	17	0.75	29	29	21	0	8,390	0	0	0	0	0
20	2.73	17	0.75	30	29	21	0	7,010	0	0	0	0	0
21	2.73	17	0.75	30	29	21	0	5,738	0	0	0	0	0
22	2.73	17	0.75	30	29	21	0	4,247	0	0	0	0	0
23	2.73	17	0.75	30	29	21	0	2,767	0	0	0	0	0

Note: 1. Target value represents the discount for reference speed based on different intersection density.

2. Light Traffic Daytime Speed is the average of the highest 2 speeds during 14 daytime hours (6am-8pm). In the above case, hour 18 (6pm-7pm) and 19 (7pm-8pm) with speed 28mph and 29mph are the highest 2 speeds during the 14 hours.

3. Target speed is the light traffic daytime speed multiplied by target value.

4. Travel time difference is the travel time difference between average speed and light traffic daytime speed. Use 0 when the calculated value is less than 0, meaning that the average speed is faster than the light traffic daytime speed and there is no delay.

5. Same as 4, but use target speed instead of light traffic daytime speed.

From Turner, S., and Qu, T. *Developing Twin Cities Arterial Mobility Performance Measures Using GPS Speed Data*. Prepared for Minnesota Department of Transportation. Texas A&M Transportation Institute, College Station, TX, 2013. <http://www.dot.state.mn.us/research/TS/2013/201314.pdf>. Reproduced with permission of Texas A&M Transportation Institute.

Table A3. Travel Time Index and Planning Time Index Calculation

Hour	Hourly Vehicle Miles Traveled (a)	Average Speed (b)	80 th percentile Speed (c)	Light Traffic Daytime Speed (d)	Travel Time Index (e) $= \max(\frac{60}{(b)}, \frac{60}{(d)}, 1)$	Planning Time Index (80 th percentile) (f) $= \max(\frac{60}{(c)}, \frac{60}{(d)}, 1)$
0	1,464	30	---	29	Max((60/30)/(60/29),1) =1	---
1	896	30	---	29	1.00	---
2	617	30	---	29	1.00	---
3	579	30	---	29	1.00	---
4	952	30	26	29	1.00	1.09
5	2,425	28	23	29	1.02	1.23
6	5,788	27	21	29	1.07	1.36
7	8,617	25	18	29	1.13	1.61
8	8,679	26	19	29	1.12	1.51
9	8,956	24	17	29	1.17	1.65
10	10,221	24	16	29	1.20	1.76
11	11,775	24	15	29	1.21	1.86
12	12,403	24	16	29	1.19	1.80
13	12,422	25	17	29	1.16	1.67
14	13,829	24	16	29	1.20	1.75
15	16,369	23	16	29	1.23	1.78
16	17,989	23	15	29	1.23	1.90
17	15,670	24	16	29	1.18	1.82
18	10,887	28	20	29	1.02	1.43
19	8,390	29	20	29	1.00	1.43
20	7,010	30	23	29	1.00	1.23
21	5,738	30	16	29	1.00	1.82
22	4,247	29	---	29	1.00	---
23	2,767	29	---	29	1.00	---
Weighted Average¹					1.14	1.68
Weighted Average (AM Peak): hour 6,7,8					1.11	1.51
Weighted Average (PM Peak): hour 16,17,18					1.16	1.76

Note: 1. Weighted Average Travel Time Index use Hourly Vehicle Miles Traveled (a) as weights.

From Turner, S., and Qu, T. *Developing Twin Cities Arterial Mobility Performance Measures Using GPS Speed Data*. Prepared for the Minnesota Department of Transportation. Texas A&M Transportation Institute, College Station, TX, 2013. <http://www.dot.state.mn.us/research/TS/2013/201314.pdf>. Reproduced with permission of Texas A&M Transportation Institute.

Table A4. Target Values by Land Use

Intersection Density (No. per Mile)	Target Value (As % of Light Traffic Speed)
Less than 2	100
2-4	90
4-8	85
More than 8	75

APPENDIX B

ADJUSTMENT FOR MISSING DATA AT CONTINUOUS COUNT STATIONS

Of the 29 CCS directions of interest to this study, 7 were missing data for a few months (6 were missing 3 months of data, and 1 was missing 4 months of data). Their effects on the TOD traffic volume profiles were not known, and hence they were investigated. The methodology used to adjust for the missing data, comparison of the unadjusted and adjusted hourly TOD traffic volume profiles, conclusions, and recommendations of this investigation are presented here.

Methodology Used for Adjustment

All CCSs had data for 3 months: April, May, and June 2013. Therefore, these data were used as a base for comparing the different months of data for the CCSs.

1. The monthly average daily traffic was calculated from the available data for all CCSs.
2. For each month (where data were available) and each CCS, a ratio was computed from these monthly average daily traffic volumes divided by the average monthly traffic from April-June 2013.
3. Correlation coefficients were determined across all CCSs from all the monthly ratios available.
4. For each CCS with missing data, good matches with CCSs with complete data were determined. All correlations above 0.9 were considered to indicate good matches.
5. For each CCS with missing data, average monthly factors from all of its “good match” CCSs with a full year of data were calculated and applied.
6. For each CCS with missing data, TOD traffic volume profiles with both the unadjusted data and the adjusted data were compared by graphing and calculating the correlation coefficients.

Comparison of TOD Profiles

Among the 7 CCSs with missing data, the smallest correlation between the unadjusted and the adjusted hourly TOD volume profiles was 0.999987. This was for CCS 781531-West, which had 3 months of data missing. The unadjusted and adjusted profiles are shown in Figure B1.

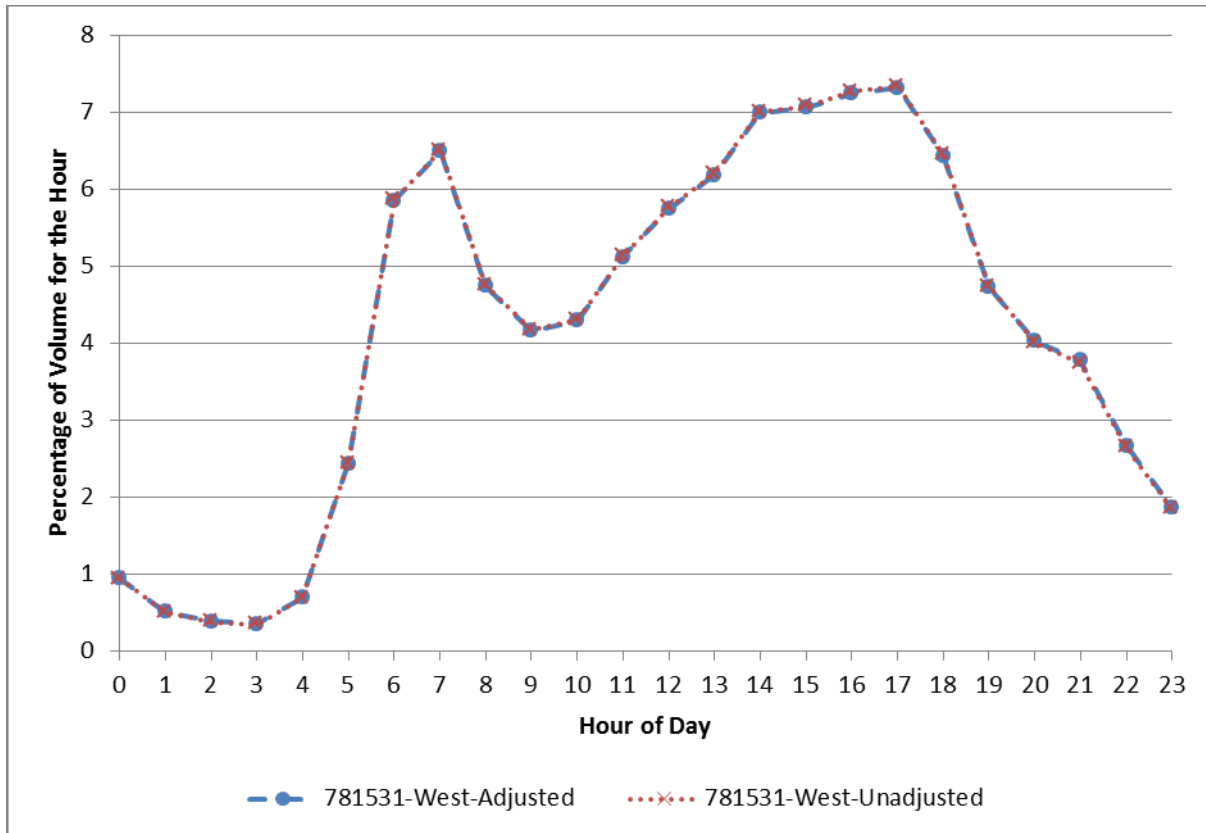


Figure B1. Adjusted and Unadjusted Time-of-Day Traffic Volume Profiles for CCS 781531-West.

Conclusions and Recommendations

1. A few months (3 or 4 months in this study) of missing data do not affect the TOD profile. Such instances of missing data should be ignored.
2. A few months (3 or 4 months in this study) of missing data will impact the AADT and hence VMT. As much as a 5% difference was observed in this study for 3 or 4 months of missing data. Therefore, the published AADT should be used even for the CCSs rather than calculating it from the available data unless they are adjusted suitably.

APPENDIX C

VISUAL DATA QUALITY ASSESSMENTS

The due diligence visual data quality assessments shown in Table C1 were performed on speed data from Bluetooth, INRIX, and NPMRDS and on volume data.

Table C1. Details of Due Diligence Assessment Graphs

No.	X-axis	Y-axis	Legend	One Graph per Group of:
1	Time of Day	Raw Speed	Date	Each TMC
2	Time of Day	Average Speed	TMC	Each Segment
3	Time of Day	Average Speed	TMC	Each Segment and DOW
4	Time of Day	Average Speed	Segment	-
5	Time of Day	Average Speed	Segment	Each DOW
6	Time of Day	Average Speed	TMC	-
7	Time of Day	Average Speed	TMC	Each DOW
8	Time of Day	Average Speed	DOW	Each TMC
9	Time of Day	Average Speed	DOW	Each Segment
10	Time of Day	Raw Volume	Date	Each Site
11	Time of Day	Average Volume	DOW	Each Site
12	Time of Day	Average Volume	Site	-
13	Time of Day	Average Volume	Site	DOW
14	Volume	Speed	-	Segment

TMC = Traffic Message Channel; DOW = day of week.