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Improving the Identification and Characterization of Arterial Congestion Bottlenecks

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16. Abstract:

Performance-based and data-driven approaches are increasingly employed by transportation professionals to provide a strong foundation for making sound decisions and for optimizing investments. This study developed and evaluated one such method for identifying and ranking traffic bottlenecks. Bottleneck analysis tools currently available to the Virginia Department of Transportation (VDOT) typically analyze links along a roadway and do not consider the conditions on the side streets at intersections. This study proposed a new sketch planning bottleneck analysis and ranking method for arterial intersections using a node-link approach that examines all intersection approaches. The methodology uses widely available datasets such as probe vehicle speeds and annual average daily traffic (AADT). Impacts of different congestion threshold speeds and queue estimation methodologies were studied. A tool was developed to summarize, visualize, and drill down the results interactively.

A case study was conducted using a Northern Virginia urban arterial network with 245 nodes, and an expert panel validated the study results with their field observations. Their comments and feedback showed high confidence in the results, pointing to the success of this proof-of-concept study. Additional feedback from VDOT, the Virginia Office of Intermodal Planning and Investment (OIPI), and localities indicated their high interest in using this methodology mainly because of the quantitative performance measures and the ability to support data-driven decision making. Their intended use cases include improved planning, funding, and evaluation of bottleneck mitigation solutions across their region and the state. Several lessons were learned during this study and documented, which will help to scale up this methodology for potential statewide adoption.

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FINAL REPORT

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DISCLAIMER

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ABSTRACT

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FINAL REPORT

IMPROVING THE IDENTIFICATION AND CHARACTERIZATION OF ARTERIAL CONGESTION BOTTLENECKS

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INTRODUCTION

Performance-based and data-driven approaches are increasingly being employed and encouraged by Virginia's Commonwealth Transportation Board (Virginia Department of Transportation [VDOT], 2018a) and VDOT's executive management (Brich, 2018). VDOT is also increasingly implementing such approaches in various applications including project prioritization, programming, congestion and safety solution identification, and operational decision making (Nguyen et al., 2018; VDOT, 2016, 2018a, 2018b, 2018c). However, in the absence of appropriate data, methodology, and tools, professionals are forced to rely on subjective information such as citizen complaints and limited field observations (McDermott, 2018). This study explored the use of a new, high resolution traffic data source and developed and evaluated a new methodology toward improved data-driven analysis of arterial traffic bottlenecks.

Bottlenecks constrain traffic flow and cause traffic congestion. Identifying bottleneck locations and understanding their properties such as when, how long, how often, how intensely, and why congestion is present are the first steps in bottleneck remediation (Federal Highway Administration [FHWA], 2017). VDOT currently has access to three main data-driven bottleneck analysis tools: (1) the Regional Integrated Traffic Information System (RITIS) tool (hereinafter the "RITIS tool"); (2) the FHWA Congestion Bottleneck Identification (CBI) tool (hereinafter the "CBI tool"); and (3) the Iteris Performance Management System (iPeMS) tool (hereinafter the "iPeMS tool"). All of these tools have different strengths and limitations. VDOT's Traffic Engineering Division (TED), Transportation Mobility and Planning Division (TMPD), and Operations Division (OD) identified the following major limitations of these tools:

1. The RITIS and CBI tools have capitalized on the high coverage and quality of vehicle probe–based speed data but do not directly consider the traffic volumes exposed to congestion. In contrast, the iPeMS bottleneck identification module uses both the traffic volume and speed data from roadway detectors. However, the relatively sparse detector coverage in Virginia and data quality issues have severely restricted the practical utility of the iPeMS tool for VDOT.

2. All of these tools analyze the traffic network as links. Although this approach is reasonable for freeways, arterial junction analysis will be better served by a link-node

approach whereby all the links approaching a node are analyzed together rather than separately. The traffic impacts both from and to the side streets and the turning movements in an arterial network are expected to be captured better with the link-node approach.

3. The CBI tool can analyze only one corridor at a time.

Staff from these divisions formed the technical review panel (TRP) for this study and also identified two new opportunities to develop an enhanced tool:

1. Although the RITIS tool was developed using probe speed data based on the Traffic Message Channel (TMC) network, INRIX offers more granularity and higher coverage with its XD network. VDOT has access to the XD speed data and archives them within iPeMS.

2. A methodology based on vehicle delay as the primary performance measure could potentially be applied to both freeways and arterials, as well as the interchanges that connect these two networks.

VDOT's TED, TMPD, and OD approached the Virginia Transportation Research Council (VTRC) to conduct a study to overcome the above-mentioned limitations and exploit the emerging opportunities.

PURPOSE AND SCOPE

The main objectives of this study were as follows:

1. Develop a new methodology to identify and characterize bottlenecks using the link-node concept and vehicle delays calculated from the XD network-based vehicle probe speeds.

2. Apply the methodology to a study network as a proof of concept and validate the results.

3. Identify major use cases and users for the results of this new methodology.

Additional performance measures and visualizations were developed to summarize and drill down the analysis results. The scope of the study focused on arterial networks, with limited application to and integration with freeways and interchanges. The scope of the methodology was established as bottleneck ranking for network screening purposes at the sketch planning level.

METHODS

Five main tasks were performed to achieve the study objectives:

1. Review the literature.
2. Develop a bottleneck identification methodology.
3. Identify the study network, prepare the data, and apply the methodology.
4. Analyze the case study results.
5. Validate the results, and identify potential use cases.

Task 1: Review the Literature

The TRP directed the researchers to focus the literature review on the three bottleneck tools identified earlier and available currently for VDOT's use (i.e., the RITIS tool, CBI tool, and iPeMS tool) in order to understand and document their strengths and limitations. The reviewed literature included the documentation of the three bottleneck tools; the pre-publication draft of NCHRP Report 854: Guide for Identifying, Classifying, Evaluating, and Mitigating Truck Freight Bottlenecks (Ahanotu et al., 2017); *Freight Performance Measure Approaches for Bottlenecks, Arterials, and Linking Volumes to Congestion Report* (Margiotta et al., 2015); *Truck Freight Bottleneck Reporting Guidebook* (FHWA, 2018), prepared for the Moving Ahead for Progress in the 21st Century Act (MAP-21); and the American Transportation Research Institute's (ATRI) list of truck bottlenecks (ATRI, n.d.).

Task 2: Develop Bottleneck Identification Methodology

This task entailed the following five sub-tasks:

1. Identify and develop performance measures of interest.
2. Identify data sources, and gather data.
3. Develop the calculation steps to turn input data into final performance measures.
4. Program the calculations into computer code.
5. Develop visualizations to support analyses.

Performance measures were selected from VDOT's *Traffic Operations and Safety Analysis Manual (TOSAM)* (VDOT, 2015). Performance measures in addition to vehicle delay were developed. Various data sources of interest were identified throughout the study. Specifically, gathering the probe speed data from iPeMS required developing computer scripts. Based on the underlying network segments and the data available, two queue calculation methods were developed in this task. The entire calculation methodology was programmed in Python, an open source language, as requested by the TRP. Several iterations of debugging were performed, accounting for the improved understanding of the underlying data and the performance measures during the study. To summarize and analyze the results, a visualization tool was developed in Tableau since its reader software is deployed widely on VDOT computers, is available as a free download for others, and provides drill down capabilities to users.

This task and Tasks 3 through 5 were carried out in an iterative manner to adjust the new methodology and computer codes to the data available, analysis results, and validation feedback. One main reason for these iterations was a major INRIX map update in May 2017 from Version 16.2 to Version 17.1. In consultation with the TRP, the researchers decided to use the newer version, which would be more beneficial to VDOT going forward. However, this decision also restricted the amount of data immediately available for this study. Therefore, over the life of the study, data for additional time periods were incrementally obtained and analyzed.

Task 3: Identify Study Network, Prepare Data, and Apply Methodology

Features of potential study network locations and some potential sites were identified in consultation with the TRP. The specific network selected for this study included the Tysons Corner and the Seven Corners areas in Northern Virginia. For this network, all relevant data were gathered and prepared. These datasets and their sources included the underlying XD segment shapefile (for XD Version 17.1) and XD reference speeds from INRIX; XD speed data and confidence scores from iPeMS; posted speed limits (PSLs) from VDOT and Arlington shapefiles; annual average daily traffic (AADT) from VDOT's TED; national average traffic volume profiles from the Texas A&M Transportation Institute (TTI) (Schrank, 2014); and Google Maps. Data preparation included identification of the nodes (intersections) and links (approaches to each intersection); order of XD segments on each approach; conflation of the different datasets; data quality screening; and imputation of missing data. Applying the methodology involved the management of hardware, software, input data, and scripts.

Task 4: Analyze Case Study Results

The analysis of results consisted of two concurrent components: (1) sensitivity analysis of outputs to specific input parameters and calculation methods, and (2) examination of trends and anomalies in all of the performance measures both individually and together across different approaches, nodes, approach or node features, dates, days of the week, and times of the day. Complete details of the bottleneck identification methodology are presented in the "Results and Discussion" section. However, two specific aspects need to be explained here to enable discussion of the sensitivity analyses: threshold speeds and queue calculation method.

First, congestion identification and delay calculations required definitions of reference speed and congestion threshold speed. In this study, if a segment speed for a given timestamp was less than the threshold speed, then the segment was determined to be congested (i.e., in a bottleneck state) at that time. Then, delay was calculated for that segment and time period in comparison to a reference speed. For example, congestion may be defined as any speed below 60% of the PSL, and delay may be calculated with reference to the PSL. Many reference speeds are used in the literature, as noted by Venkatanarayana (2017) in a report on arterial system performance measures. Venkatanarayana employed three reference speeds: PSL, reference speed provided by the data vendor, and light traffic speed (LTS) (defined as the average traffic speed on the segment between 10 P.M. and 5 A.M.). These same three speeds were selected for this study. Approach and intersection delays and other performance measures were then calculated from their constituent segments.

Second, two methods of calculating queues were developed in this study. The entire road network was first divided into nodes and approach links. Given that an approach to a node can consist of more than one XD segment and any XD segment with traffic speeds below the threshold was deemed congested, two queue length calculation methods were used:

1. *Method I:* Any congested XD segment on the approach contributed to the queue length. This method is sensitive to any access-related congestion on the approach.

2. *Method II:* Starting from the XD segment closest to a node, only the congested, contiguous XD segments on the approach contributed to the queue length. This method strictly assesses the queues starting at the node.

Under both methods, all the performance measures, including delay, were calculated only for the contributing XD segments. These two aspects (threshold speed and queue calculation method) and their respective variations resulted in six combinations of interest for sensitivity analyses.

The individual performance measures were inspected for anomalies such as too high or too low a value, and combinations of measures were cross-checked for their alignment with theoretical expectations and known field observations. For example, most intersections and approaches are expected to exhibit heavier congestion during weekday peak periods and relatively no congestion overnight. As another example, delays and vehicle miles traveled (VMT) are expected to increase and decrease together and are usually expected to be higher on congested freeway segments than on arterial segments. Anomalies and trends were examined using summary tables, heatmaps, charts, and maps. Specific dimensions, performance measures, and checks performed included the following:

- *Duration and frequency of congestion:* This dimension pertains to the amount of time that congestion persists before returning to an uncongested condition, the number of bottleneck occurrences, and the gap time between the bottleneck state and non-bottleneck state.

  — Are there too many bottlenecks with short durations?

  — Are there too few bottlenecks, with or without long durations?

  — How did bottlenecks compare with predominantly expected time-of-day and day-of-week patterns?

  — Did any nodes or approaches exhibit unusual patterns of bottlenecks and gaps such as on/off/on/off for short periods, say every 15 minutes?

- *Intensity:* This dimension relates to the relative severity of congestion at the intersections and on intersection approaches.

  — Examine time-of-day, day-of-week, and day-to-day trends in delay, VMT, normalized delay, and normalized VMT.

- *Variability:* This dimension relates to the changes in bottleneck conditions by time of day, day of week, and approach.

  — Examine time-of-day and date trends for each measure across intersections and across approaches within an intersection.

  — Examine the distribution of different performance measures across facility type (freeways, arterials, ramps), features (AADT, length), and data characteristics (completeness of XD segments and AADTs, quality).

- *Extent:* This spatial dimension relates to the length and the number of segments affected by the bottlenecks.

  — Examine the trends of spillbacks and queue lengths across time and space.
  — Examine the impact of short approaches on spillbacks and queue lengths.

- *Combinations of Measures:*

  — Examine the scatter plot matrix of different measures to understand their correlations.

Task 5: Validate Results and Identify Potential Use Cases

Since the methodology developed in this study was fundamentally different from existing tools, their results could not be directly compared. Likewise, field data collection to validate results across a broad cross section of networks would not be realistic from a cost or staffing perspective. Therefore, a quantitative, statistical validation of the results of this study was not possible. To overcome these challenges, an expert panel was employed to evaluate the value of the tools and the perceived validity of the bottleneck ranking results as compared to field observations. Demonstrating these results to the expert panel and other transportation experts in Virginia, the research team solicited additional performance measures and metadata needed for improving the effectiveness of the visualizations. Potential implementation concerns regarding the methodology of this study and visualizations also were sought.

Discussions with the TRP and the advisory panel throughout the study and specifically during validation efforts revealed the major use cases for this methodology. Between June and August 2018, the researchers also presented the study to and sought feedback from VDOT district traffic engineers (DTEs), the Virginia Office of Intermodal Planning and Investment

(OIPI), and a broader audience at the 2018 National Traffic Monitoring and Exposition Conference (NaTMEC) held in Irvine, California.

RESULTS AND DISCUSSION

Task 1: Literature Review

This task focused primarily on reviewing the three bottleneck tools (the RITIS tool, CBI tool, and iPeMS tool) currently available to VDOT; reviewing recent freight bottleneck studies; and investigating the speed threshold for differentiating between congested and uncongested traffic conditions.

Summary of Existing Tools

RITIS Tool

The RITIS tool uses private sector probe travel time data for congestion analysis and bottleneck ranking (University of Maryland Center for Advanced Transportation Technology [CATT] Lab, 2018). The availability of these probe data sources (INRIX, HERE, TomTom) varies by state, analysis period, and road; and data are analyzed using TMC segments. A TMC segment is considered congested when the average travel speed on the segment during an analysis interval is below 60% of the vendor reference speed for the segment. Bottlenecks are ranked based on an impact factor that is calculated as the sum of the queue lengths over the duration of the bottleneck. This base impact factor considers the average duration and extent of congestion throughout the analysis period. In addition to bottleneck duration and maximum queue length, weighted impact factors are calculated, namely, base impact weighted by speed differential (i.e., difference between free-flow speed and observed speed); base impact weighted by congestion (i.e., measured speed as a percentage of free-flow speed); and base impact weighted by total delay (i.e., difference between free-flow speed and observed speed multiplied by AADT).

Different graphs and tables are produced to illustrate the summary and details of bottleneck and congestion trends, as shown in Figure 1. For example, the bottleneck ranking table (center-top in Figure 1) displays a list of approximate bottleneck locations during the analysis period and a summary of performance measures for all bottlenecks at each of those locations. The Map view (lower left in Figure 1) shows selected bottleneck locations, maximum queue length, and total number of traffic incidents during the analysis period. The Timeline view (lower right in Figure 1) shows bottleneck elements and traffic incidents occurring at the selected location in a timeline-style graphic. An element is a combination of sequential congestion occurrences with identical queue head locations. Each row on the timeline represents a date, and elements occurring at a specific time are displayed as a colored box. The horizontal width of the box indicates the duration of the element, and the color indicates the maximum queue length for the element. Other views such as Elements Graph, Elements Table, and Time Spiral are also provided to explore the spatial and temporal characteristics of bottlenecks. The tool also provides the option to export the results as comma-separated values (i.e., csv format).

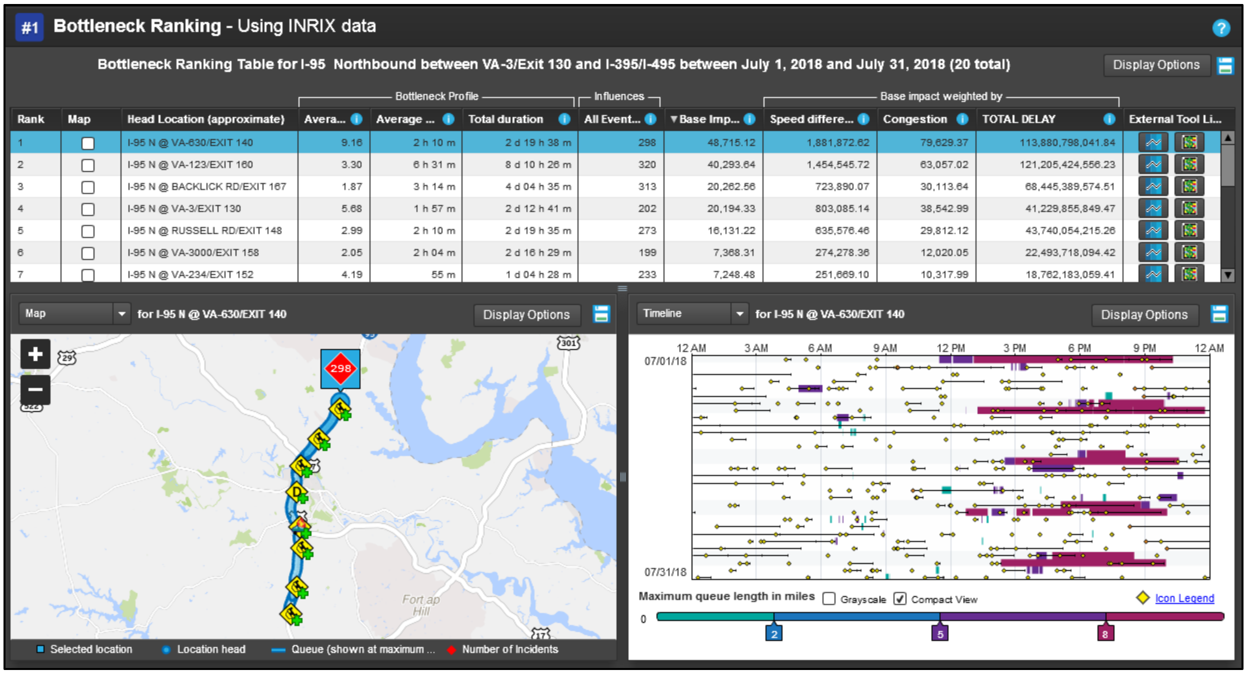
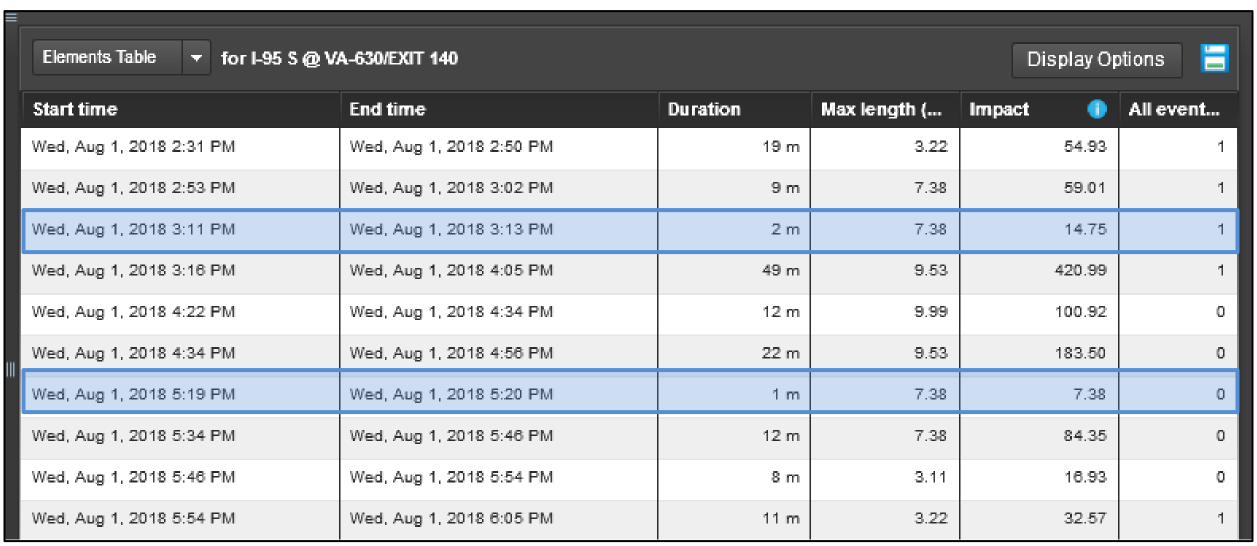


Figure 1. RITIS Bottleneck Ranking Dashboard Using INRIX Data. The bottleneck ranking table (center-top) displays a list of bottlenecks and their performance measures. The Map view (lower left) shows select bottleneck locations, maximum queue length, and total number of traffic incidents during the analysis period. The Timeline view (lower right) shows bottleneck elements and incidents occurring at the select location in a timeline-style graphic.

The RITIS tool does not compare time-of-day and day-of-week variations of each performance measure. The minimum analysis period is 1 day. The duration of an element can be as short as 1 or 2 minutes, as shown in Figure 2 (highlighted in blue). Such short congestion occurrences might not be considered a bottleneck in some operational analyses.



Elements Table for I-95 S @ VA-630/EXIT 140 — Display Options

Start time	End time	Duration	Max length (...	Impact	All event...
Wed, Aug 1, 2018 2:31 PM	Wed, Aug 1, 2018 2:50 PM	19 m	3.22	54.93	1
Wed, Aug 1, 2018 2:53 PM	Wed, Aug 1, 2018 3:02 PM	9 m	7.38	59.01	1
Wed, Aug 1, 2018 3:11 PM	Wed, Aug 1, 2018 3:13 PM	2 m	7.38	14.75	1
Wed, Aug 1, 2018 3:16 PM	Wed, Aug 1, 2018 4:05 PM	49 m	9.53	420.99	1
Wed, Aug 1, 2018 4:22 PM	Wed, Aug 1, 2018 4:34 PM	12 m	9.99	100.92	0
Wed, Aug 1, 2018 4:34 PM	Wed, Aug 1, 2018 4:56 PM	22 m	9.53	183.50	0
Wed, Aug 1, 2018 5:19 PM	Wed, Aug 1, 2018 5:20 PM	1 m	7.38	7.38	0
Wed, Aug 1, 2018 5:34 PM	Wed, Aug 1, 2018 5:46 PM	12 m	7.38	84.35	0
Wed, Aug 1, 2018 5:46 PM	Wed, Aug 1, 2018 5:54 PM	8 m	3.11	16.93	0
Wed, Aug 1, 2018 5:54 PM	Wed, Aug 1, 2018 6:05 PM	11 m	3.22	32.57	1

Figure 2. Elements Table of RITIS Bottleneck Ranking Tool. Each row represents an element at a select bottleneck location. Two elements with short durations are highlighted.

Although average AADT is used as a surrogate for volume to calculate the delay-weighted impact, this metric does not reflect the variability in observed traffic volumes within a day. Studies by the research team also found that this tool may identify a very long stretch of roadway (more than 20 miles) as one bottleneck, which makes it difficult to identify appropriate mitigation solutions.

CBI Tool

The CBI tool was developed under FHWA sponsorship to compare congestion and bottlenecks in detail and emphasizes annual bottleneck intensity (Hale et al., 2016). Inputs for the CBI tool are probe travel time data files, which can be downloaded from RITIS. The tool includes two basic modes of analysis: congestion mode and bottleneck mode. The bottleneck mode ranks bottlenecks based on a number of measures including duration, intensity, variability, and extent. The numeric performance measures are split into daily and annual calculations. The CBI tool uses an annual reliability matrix (ARM) to integrate the reliability concept and develops a bottleneck intensity index (BII) to quantify the intensity of delay. An example of an ARM diagram is given in Figure 3.

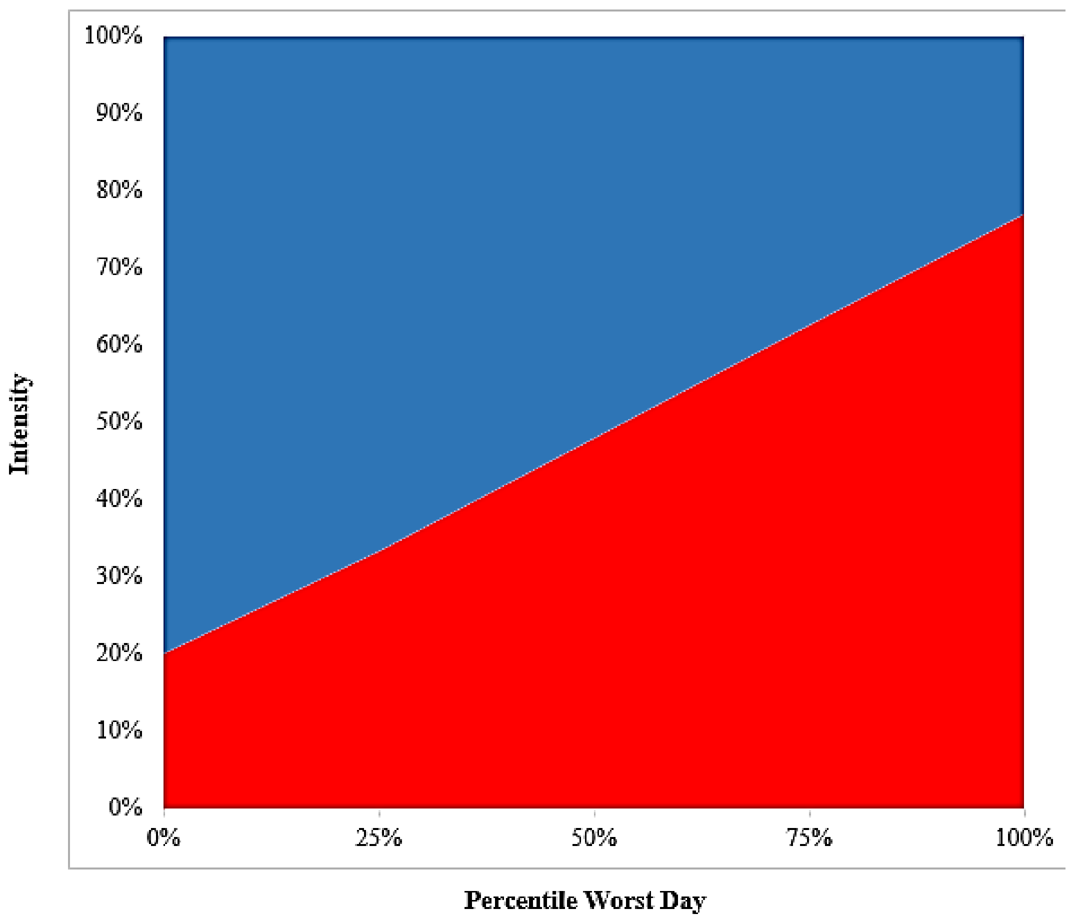


Figure 3. Annual Reliability Matrix (ARM) Diagram Based on Bottleneck Intensity. The red area is defined as congested, and the blue area is defined as uncongested. The size and shape of the red area are used to compare the intensity and reliability of different bottlenecks.

The X-axis represents all days of an analysis year, with the best day of the year (i.e., the day with the least traffic delay) on the far left and the worst day (i.e., the day with the highest traffic delay) on the far right. The Y-axis denotes the intensity of bottlenecks. The red area is defined as congested, and the blue area is defined as uncongested. The size and shape of the red area are used to compare the intensity and reliability of different bottlenecks. BII is a numerical measure developed to quantify the ARM into a single number, and its value represents a delay level below which 85% of the ARM's red area exists.

The 85th percentile BII is explained to be more effective than 85th percentile delay for comparing bottlenecks. The BII computation explicitly reflects a summation of delay values throughout the year, whereas the percentile delay simply needs to be larger than a portion of other days' delays. The CBI tool includes a wavelet filtering method to filter out the delays that appear to be unrelated to congestion (e.g., delay caused by traffic signals) on arterials. When the "Signalized Arterial" checkbox is selected, the tool will automatically invoke the wavelet method to adjust the input speeds. However, the documentation contains few details on the wavelets, their benefits, or any concerns.

The CBI tool was designed to analyze bottlenecks on one corridor at a time and was not designed for direct network level analysis. The calculation of the ARM does not consider the magnitude of speed drops on the segments, and thus the overall bottleneck ranking may not be reliable. For two bottlenecks with the same amount of red area and a similar shape in the ARM diagrams, both bottlenecks would produce the same intensity measure and thus the same priority rank. However, it is possible that one of the bottlenecks was more severe than the other because of very low speeds during congestion. Additional analysis with daily and annual average speed drops is needed to compare bottlenecks with similar ARMs. The CBI tool allows users to enter a bottleneck volume to quantify the intensity of bottlenecks.

Figure 4 shows the CBI tool interface. Compared to the RITIS tool, the CBI tool has fewer visualization options. The tool provides a Google Maps feature that allows users to view the most congested locations along with the spatio-temporal matrix (STM) (same as the congestion scan heatmap in RITIS), but this feature is available only when an STM diagram is displayed on the screen. It is not possible for users to export the analysis results.

iPeMS Tool

The major differences between the iPeMS tool and the other two tools are that the iPeMS tool uses speed and volume data from roadside detectors as opposed to probe speed data, and it evaluates only freeways. The iPeMS tool assumes that a bottleneck exists at a particular detector when there is a persistent speed drop from the current detector to the immediately upstream detector (Iteris, 2017). A bottleneck is confirmed when all of the following conditions are met: there is a speed drop of at least 20 mph, the speed at the current detector is less than 40 mph, the detectors are less than 3 miles apart, and the speed drop persists for at least 5 of any 7 contiguous 5-minute intervals.

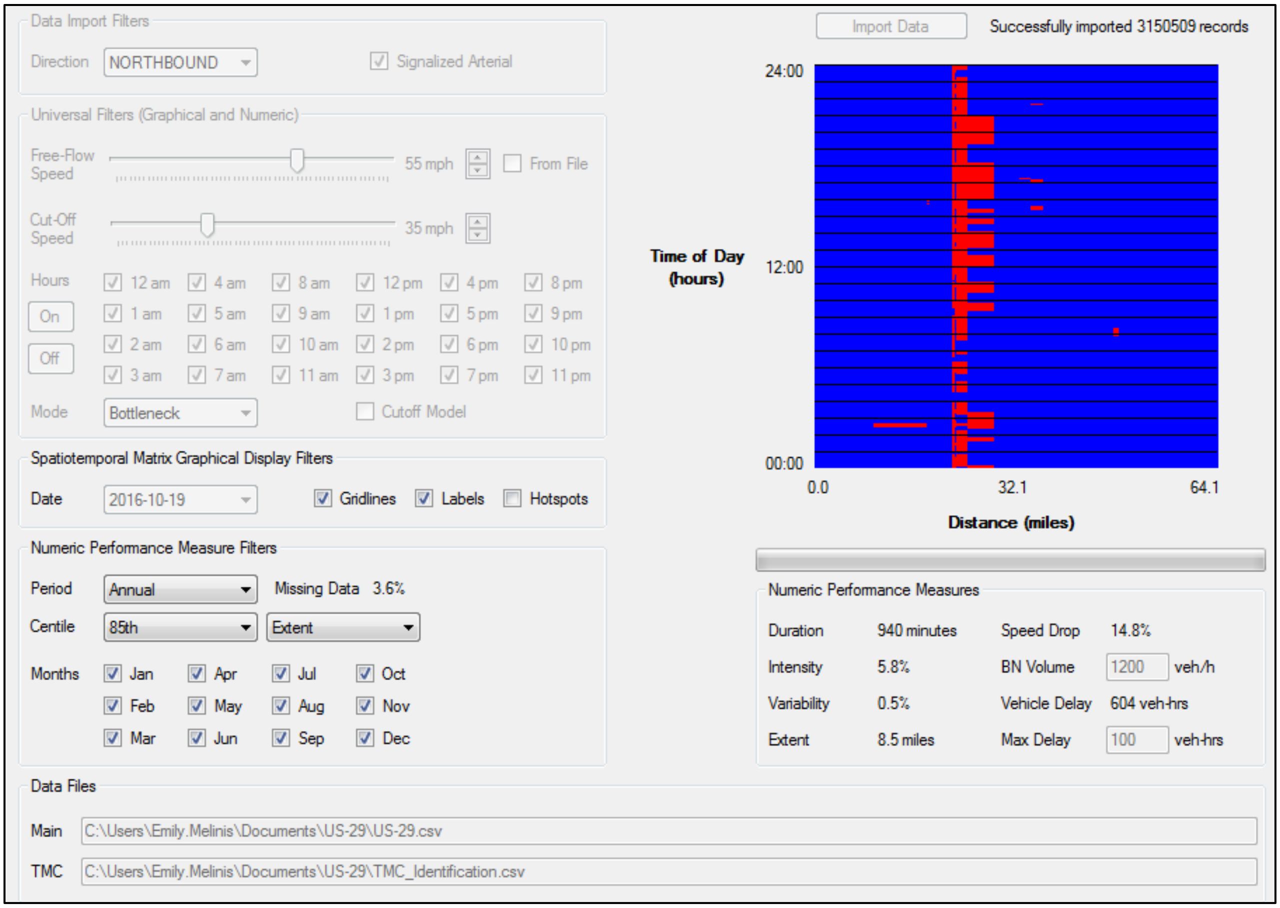
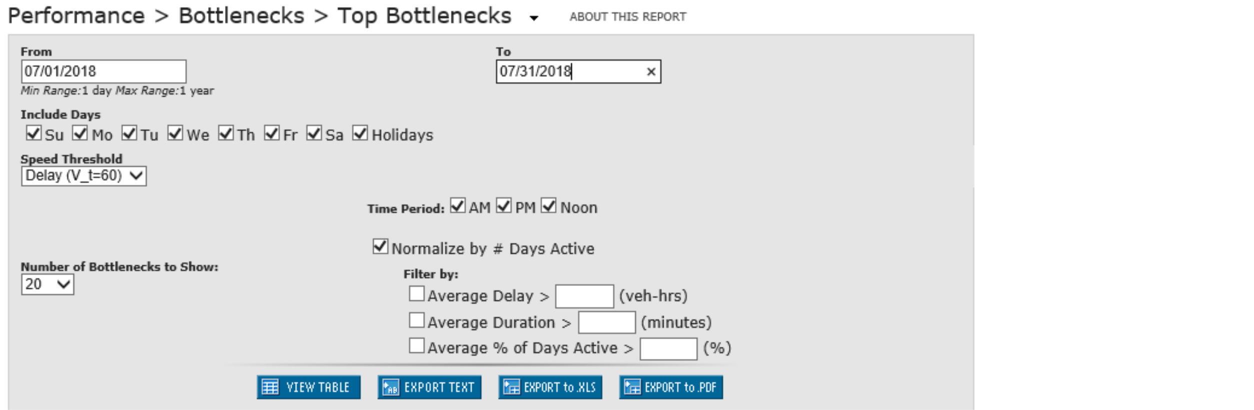


Figure 4. Interface of the CBI Tool. The left side shows the options for users to define analysis inputs, and the right side displays select performance measure results.

Performance measures including bottleneck duration, number of days that a bottleneck was observed at the location, spatial extent, and total delay are calculated for each bottleneck and summarized for each bottleneck location. These performance measures are provided in the bottleneck ranking table shown in Figure 5. However, the bottleneck analysis can be conducted only for certain times of the day: morning (5 A.M. to 10 A.M.); noon (10 A.M. to 3 P.M.); and evening (3 P.M. to 8 P.M.), and the analysis period ranges from 1 day to 1 year. Because of the constraints on the analysis period, any bottleneck lasting longer than 5 hours is separated into two bottlenecks. In addition, low spatial density and low quality of data from roadside sensors may have major adverse impacts on the results of the iPeMS tool. Compared to the RITIS and CBI tools, the iPeMS tool lacks robust visualization capabilities. The bottleneck location can be seen from a map window.



Location									Bottleneck Characteristics			
Station	Name	Type	Shift	Fwy	Abs PM	MM	Latitude	Longitude	# Days Active	Avg Extent (Miles)	Avg Delay (veh-hrs)	Avg Duration (mins)
612291741	TSS 0066 W 04540 - 2537 WB Nor	ML	PM	I-66W OSM:42.93-75.16-W	2.600	45.427600	38.799	-77.55646	1	2.0	96.8	35.0
64251921	64EB after Industrial Park Dr	ML	PM	I-64E OSM:190.66-300.42-E	61.530	252.364600	37.15258	-76.53617	1	2.3	23.8	5.0
4071361	VA 144 Temple Ave; SR 36 to Ch	ML	NOON	VA-144S OSM:0.01-4.57-S	2.410	2.418600	37.25235	-77.37387	1	2.6	169.9	60.0
119633521	I-64 E Mainline at MM 115.0	ML	AM	I-64E OSM:87.14-187.46-E	27.870	115.035600	38.02898	-78.59075	1	1.6	49.0	30.0
44042241	264WB at Mount Trashmore W Mai	ML	AM	I-264W OSM:-0.00-25.21-W	17.270	17.111600	36.83311	-76.1254	1	0.5	135.5	50.0
85908831	I-95 S Mainline at MM 76.3	ML	AM	I-95S OSM:-0.00-178.56-S	76.270	76.330600	37.5528	-77.44329	1	0.8	24.3	20.0
44018241	264WB at Witchduck W Main Lane	ML	AM	I-264W OSM:-0.00-25.21-W	15.320	15.180600	36.8389	-76.15942	1	2.1	968.9	80.0
19008681	29-0 Franconia Springfield Pkw	ML	NOON	VA-289W OSM:-0.00-3.08-W	1.000	1.074600	38.76457	-77.19997	1	3.5	22.7	30.0
15010821	VA 143 Jefferson Ave; SR 173 D	ML	PM	VA-143N OSM:15.37-36.34-N	5.720	21.098600	37.14614	-76.52575	1	5.0	72.1	45.0
14010481	US 460 County Dr; SR 109 Hicko	ML	PM	US-460W OSM:322.62-323.92-W	0.010	322.625600	37.20149	-77.33519	1	0.5	3.3	105.0

Figure 5. iPeMS Bottleneck Ranking Table. The analysis period and other options are shown at the top. The results list at the bottom provides the locations and characteristics of the top-ranked bottlenecks.

Summary

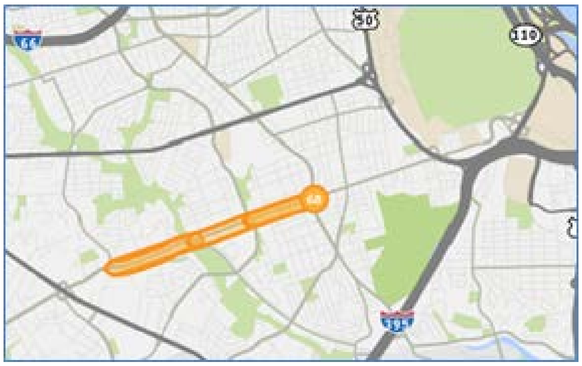
The bottleneck identification algorithms in the RITIS and CBI tools were developed from the same concept of an STM (Elhenawy et al., 2015). The algorithms use average probe speeds on the TMC segments to determine if a segment is congested at a certain time interval. When the average speed within a given cell of the STM is below the defined threshold speed, the cell is deemed a bottleneck or part of the bottleneck.

All three tools lack the capability to analyze variability of bottlenecks. The performance measures in the RITIS tool cannot reflect variabilities by time of day and day of week; the CBI tool focuses on revealing annual trends; and the iPeMS tool is limited to certain time periods. All three tools use link-based ranking algorithms, which may not identify problematic intersections since the performances of side streets are not included in the analysis. For example, in the RITIS tool, bottlenecks are evaluated by the aggregation of queue length over time on a congested link. Each approach of an intersection is ranked separately in this link-based ranking, as shown in Table 1 and Figure 6.

Table 1. Sample Bottleneck Ranking of the Four Approaches at One Intersection

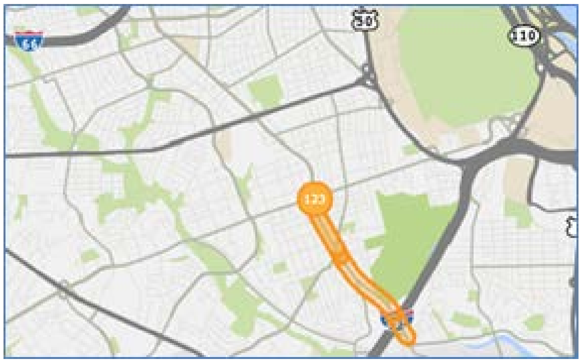
Ranking Method	Rank	Bottleneck Location	Impact (mile-minute)
Ranks of each approach among all identified link bottlenecks	46	VA-244 W at VA-120/S GLEBE RD	1475.12
	68	VA-244 E at VA-120/S GLEBE RD	1165.29
	94	VA-120 S at VA-244/COLUMBIA PIKE	902.95
	123	VA-120 N at VA-244/COLUMBIA PIKE	645.98
Rank of intersection among all clusters	13	Junction of VA-244 and VA-120 (combining all 4 approaches)	4189.34

(a)



(b)

(c)



(d)

(e)

Figure 6. Sample Intersection Bottleneck Ranks in RITIS Tool: (a-d) approaches ranked separately; (e) depiction of all approaches ranked as one cluster. Results of analyzing the Arlington County, Virginia, roadways for August 2017.

The ranks of individual approaches in Table 1 ranging from 46 to 123 do not indicate a high priority for improvement investment at this intersection. However, when the impacts of all four approaches are combined using a link node–based ranking instead (Figure 6 and the last row of Table 1), the combined impact ranks around 13th in relation to other bottlenecks, identifying a more prominent congestion problem that would otherwise be missed.

Other Bottleneck Reports

Freight bottleneck studies were also examined, owing to their increased, ongoing emphasis since MAP-21. ATRI publishes the top 100 truck bottlenecks in the nation annually (ATRI, n.d.). Commercial truck GPS records are used to estimate traffic speeds for each highway location. Hourly total truck delays are calculated using a threshold speed of 55 mph and truck volumes (presumably also from the GPS records) and summed across all 24 hours of a day to produce a "total freight congestion value." Given their focus on highways, multiple approaches converging at a node may not have been a high priority, but such a perspective is essential for accurately analyzing arterial bottlenecks.

According to the *Truck Freight Bottleneck Reporting Guidebook* (FHWA, 2018), MAP-21 mandated that state departments of transportation (DOTs) analyze and report freight bottlenecks on the interstates and may include "other roadways that the State determines to be vital to the movement of truck freight." Citing 23 CFR Part 490, a truck freight bottleneck is defined as "a segment of roadway identified by the State DOT as having constraints that cause a significant impact on freight mobility and reliability." The guidebook further states that the bottleneck identification is not a one-size-fits-all process and that:

> Neither Federal law nor Federal regulations prescribe a method for identifying truck freight bottlenecks. The state-of-the-practice in truck freight bottleneck identification methods ranges considerably among States and regions, with some adopting highly quantitative and data-driven analytic approaches, some relying on the expert knowledge of professionals on the ground, and others using a combination of both approaches. Agencies should choose bottleneck identification methods that match the traffic characteristics, infrastructure constraints, and impediments to efficient freight movement in their State and that fit with their State freight plan development process.

The guidebook also uses probe speed data and a total truck delay performance measure for bottleneck ranking. In addition, the guidebook associates congestion with its non-recurring causes such as incidents, severe weather, and special events.

The guidebook specifically highlights the need for expert validation of the bottlenecks as follows:

> Engagement with freight stakeholders and experts inside the State DOT or MPO should always be used to validate the bottlenecks flagged in a data-screening analysis against on-the-ground experience. This validation will be important for congestion-related bottlenecks and is essential for truck-restriction bottlenecks.

The following guidance is provided for researching unanticipated bottlenecks:

> Agencies should be prepared to review locations that either unexpectedly appear in screening results or that are conspicuously missing. . . . Data for unanticipated locations should also be examined to identify any temporal or geographic trends and or data quality issues. Scrutiny of daily, weekly, monthly, or seasonal data can reveal trends missed in an annual roll-up of performance, such as seasonal weather issues, non-recurring delays or other special circumstances. Comparing adjacent road segments can help identify data anomalies and better reveal how traffic patterns lead up to bottleneck locations. Analyzing data via histogram plots can help visually identify data quality issues like outliers and understand the nature of variation for a location.

Finally, visualizations are specifically recommended to help analysts pinpoint bottleneck causes and to identify patterns in large datasets.

Margiotta et al. (2015) in their report on freight performance measures stated: "When bottlenecks are intersections or interchanges, it is important to develop performance measures for all approaches into the intersection or interchange."

However, the intersection-level bottlenecks are not directly identified in this methodology. Instead, total delays, duration of congestion, and queue lengths are the proposed performance measures that apply readily to intersection evaluations also. The other performance measures proposed include travel time index and planning time index, which are specific to corridors.

The pre-publication draft of NCHRP Report 854 (Ahanotu et al., 2017) also closely follows the guidance in the reports by FHWA (2018) and Margiotta et al. (2015) in terms of delay performance measures, probe speed data, corridor-level analyses, analyses of patterns, visualizations, and identification of congestion causes. It clearly presents the entire methodology. Again, analyses of side streets at an intersection are not addressed.

Threshold Speed

A reference speed and a congestion threshold speed are necessary to identify congestion and to quantify delay and other performance measures. The threshold speed is also referred to as a cutoff speed. There is no consensus currently among transportation agencies and researchers on how significant a traffic breakdown must be to warrant bottleneck status. Engineering judgment is needed to define an appropriate threshold speed on a case-by-case basis to differentiate between congested and uncongested conditions (Elhenawy et al., 2015; Hale et al., 2016; Venkatanarayana, 2017). In some areas, the threshold speed could vary significantly on different segments of the same corridor. Free-flow speed, PSL, LTS (the average speed during 10 P.M. to 5 A.M.), and reference speed provided by the data vendors are commonly used as threshold speeds. On arterials, traffic signals and access points make it challenging to define threshold speeds (Remias et al., 2013). Traffic signals often cause average speeds to be below the PSL and free-flow speed. LTS also provides a desirable reference to capture total delays. The *2012 Urban Mobility Report* by the Texas A&M Transportation Institute used LTS as the threshold speed. Freeway threshold speeds were capped at 65 mph, and arterial speeds were not capped (Schrank et al., 2012). Vendor-supplied reference speeds such as INRIX reference speeds might not reflect the real traffic flow condition on some segments because of data quality issues, especially for very short segments. Vendor-supplied reference speeds can also change over time because of modifications to algorithms or data sources, and the reasons for such changes may not be documented.

The RITIS tool uses 60% of the INRIX reference speed on a TMC segment as the threshold speed for that segment, both for freeways and arterials. The INRIX reference speed is the 85th percentile of observed speed from all time periods on that segment, with an upper limit of 65 mph. The CBI tool provides users with the option to define a threshold speed. Instead of using a percentage of reference speed as a threshold, the iPeMS tool uses speed drops to identify bottlenecks. The selection of threshold speed will change the magnitude of performance measures but would not affect the delay trends for a segment. However, when the measures are aggregated and compared across a network, the results will be affected in unpredictable ways. Sensitivity analyses could be used to determine optimal threshold values.

Task 2: Bottleneck Identification Methodology

Overview of Methodology

Based on the link-node concept, this task developed a bottleneck identification methodology for arterial intersections. Bottlenecks are identified and analyzed for both approach and intersection levels. An intersection approach includes all analysis segments between the current intersection and the immediate upstream intersection. This definition of intersection approach is designed to study spillbacks at intersections. For the example intersection layout in Figure 7, Approach A of Node N1 has three segments. Each segment is assigned an "order" value to represent its relative location on the approach. The segment closest to Node N1 is assigned an order value of 1, and the order value increases by 1 for each upstream segment. This study examined the nodes on arterials and freeways where traffic in different directions merge or cross. The nodes on freeways where traffic diverges were not included in this study because of the lack of lane-level speed data needed to trace back the propagation of queues from an off-ramp to the freeway mainline.

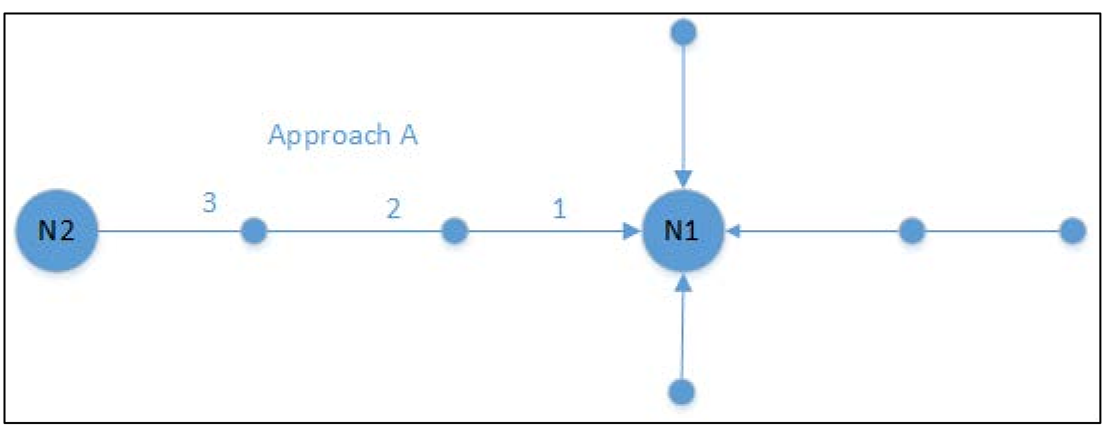


Figure 7. Example of Intersection Layout. Three segments constitute Approach A of Node N1. The segment closest to N1 is assigned an order value of 1. N1 = Node 1; N2 = Node 2.

For each segment of each approach to an intersection, the congestion condition is analyzed using the STM concept. Each cell of the STM is an analysis time interval of an analysis segment. The cell is associated with multiple attributes such as speed, volume, segment length, etc. A cell is considered congested when its average speed is lower than the defined threshold speed. The congested cells constitute bottlenecks. Congestion conditions on each intersection approach and at each timestamp are identified first to analyze intersection bottlenecks. An intersection approach bottleneck is defined using two methods:

1. *Method I:* An approach is an active bottleneck when at least one segment on the approach is congested (speed < threshold speed) during the time interval, no matter the order of segments on the approach.

2. *Method II:* An approach is an active bottleneck when the upstream segment closest to the intersection center (order = 1) is congested (speed < threshold speed) during the time interval.

Method I captures all delays along the approach, including those caused by mid-block access points. Method II focuses primarily on the approach segments closest to the intersection. An intersection is considered an active bottleneck when any of its approaches is congested. The entire methodology to identify bottlenecks and to calculate performance measures is shown in Figure 8. Each of the four steps in the flowchart is explained in more detail here.

Step 1: Collect and Prepare Data

The first step is data collection and preparation, which includes identifying data sources, collecting data, screening data for quality assurance, and handling missing data. The following data are required for the methodology illustrated in Figure 8:

- traffic speed data

- traffic volume data

- roadway inventory data (lengths and locations of segments, and locations of intersections).

The traffic speed data include the speed readings for each time interval and the reference speed such as PSLs and vendor-provided reference speeds. Traffic volume during each analysis interval is also needed for all segments, but such data are often not available. Alternatives such as AADTs with average volume profiles may be used. The locations and lengths of segments and the intersection locations are necessary to identify the intersections, approaches, and segments on each approach and to calculate various performance measures. This step also includes data quality assessments and screening. Anomalies in the data such as unrealistic speed readings (e.g., speed above 85 mph) and extremely low PSLs (e.g., 5 mph) are identified and removed, and missing data such as 15-minute average speed and volume are properly imputed based on the characteristics of the data.

Step 2: Conflate Data

This step combines the speed data with traffic volume data and roadway inventory with the objective of integrating all these data into a common data structure. Each row of the combined data contains all the relevant attributes of a segment at a certain timestamp, including speed, volume, threshold speed, segment length, downstream intersection, intersection approach associated with the segment, order on the approach, segment start point and end point, etc. This data structure allows easier calculation of delay-based performance measures for each intersection and approach. This step could be challenging as data from multiple sources are often saved in different formats and aggregated at different levels. For example, speed and volume data are often recorded in different reference systems. Techniques such as length-based weighting are needed to produce some results. In addition, data are not always available for the study segments and assumptions based on engineering judgment are needed to impute missing data. Details specific to the case study are provided in the results for Task 2.

Step 3: Identify Approach and Intersection Bottlenecks

Step 3 in Figure 8 illustrates the process of identifying bottlenecks. The logic to identify approach and intersection bottlenecks includes three parts:

1. Classify all segments into congested and uncongested segments for each time interval based on the speed readings and threshold speeds.

2. For each timestamp, identify congested approaches based on Method I or Method II.

3. If any of the approaches is congested during an analysis interval, the intersection is considered a bottleneck or part of a bottleneck based on the congestion conditions during the prior and post time intervals.

Threshold speeds for each segment are required in order to identify bottlenecks. As discussed previously, threshold speed should be carefully selected. Sensitivity analysis may be used to identify appropriate threshold speeds. The case study section explains the selection of specific threshold speeds for this study.

Step 4: Calculate Performance Measures

Performance measures are computed to quantify the duration, intensity, variability, and extent of intersection and approach bottlenecks. These performance measures are calculated differently for Method I and Method II.

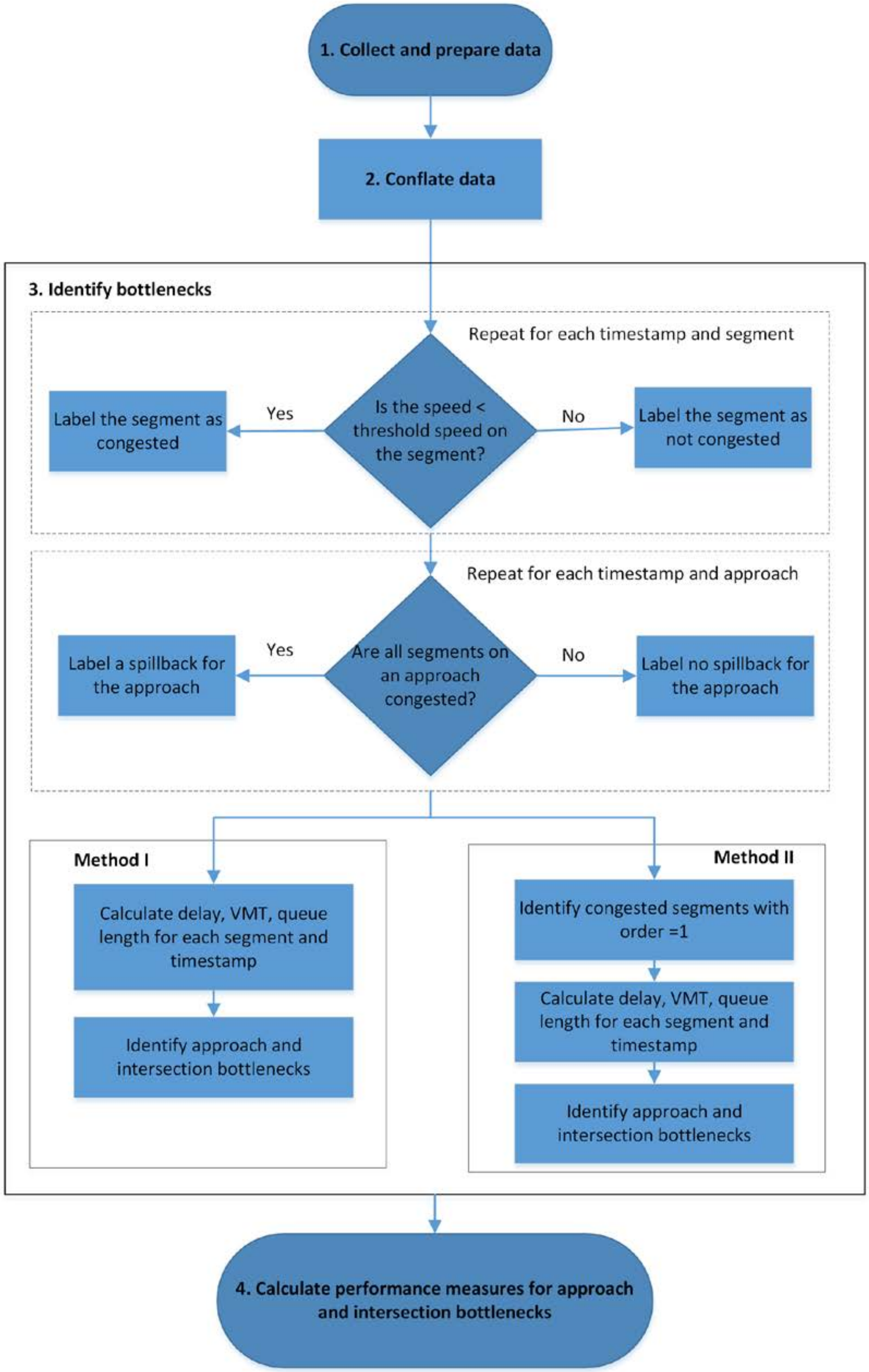


Figure 8. Overview of Bottleneck Identification Methodology

Delay. The total delay in vehicle-hours is simply the sum of the individual segment delays for the entire duration and spatial extent of the bottleneck. The delay is calculated with respect to reference speed. Delay on a segment for any time interval is:

$$d_{i,t} = V_{i,t} \times \max \ \left(0,\ \left(\frac{L_i}{v_i} - \frac{L_i}{v_{i,ref}}\right)\right) \qquad \text{[Eq. 1]}$$

where

$d_{i,t}$ = delay on segment *i* during the t^{th} time interval (vehicle-hours)
L_i = length of segment *i* (miles)
$v_{i,t}$ = travel speed on segment *i* during the t^{th} time interval (miles per hour)
$v_{i,ref}$ = reference speed on segment *i* (miles per hour)
$V_{i,t}$ = traffic volume on segment *i* during the t^{th} time interval (number of vehicles).

Delay on an intersection approach is calculated differently for each method as follows:

- *Method I:* Approach delay is the sum of delays on all segments of an intersection approach. Delay equals zero for uncongested segments.

  $$d_{a,t} = \sum_i d_{i,t} \qquad \text{[Eq. 2]}$$

  where

  $d_{a,t}$ = delay on Approach *a* during the t^{th} time interval (vehicle-hours)

  $d_{i,t}$ = delay on a segment *i* of Approach *a* during the t^{th} time interval (vehicle-hours).

- *Method II:* Approach delay is the sum of delays on all consecutive congested segments on the intersection approach. Approach delay is zero if the segment closest to the intersection center (order = 1) is not congested. For example, in Figure 7, if Segment 1 and Segment 3 on Approach A of Intersection N1 are congested but Segment 2 is not congested, then only the delay on Segment 1 is included in the calculation. If Segment 1 is not congested, then delay on Approach A is considered to be zero whether or not Segments 2 and 3 are congested.

  For both methods, delay at an intersection is the sum of delays on all its approaches:

  $$d_{n,t} = \sum_j d_{j,t} \qquad \text{[Eq. 3]}$$

  where

  $d_{n,t}$ = total delay at Intersection *N* during the t^{th} time interval (vehicle-hours)
  $d_{j,t}$ = delay on Approach *j* during the t^{th} time interval (vehicle-hours).

Since the number of segments and their lengths are not comparable across approaches, the total delay is not always the best comparative measure between different approaches or between different intersections. Therefore, normalized measures such as delay per VMT and delay per mile are also calculated.

Queue Length. Queue length measures the spatial extent of the congestion at a bottleneck. It is the sum of segment lengths of all congested segments in Method I. For Method II, queue length is calculated as the sum of segment lengths for all consecutive congested segments starting from the segment closest to the intersection center (order = 1). If the first segment on the approach (order = 1) is not congested, queue length is considered zero. Queue length is calculated for each time interval, and the maximum queue length during the bottleneck is used to quantify the spatial extent of the bottleneck. The intersection queue length is calculated as the sum of the queue lengths on all its approaches.

Spillback. Spillbacks are special cases of queue lengths. An approach is considered to have spillback for a time interval if all its constituent segments are congested during that time interval. The number of spillbacks at an intersection during a time interval is calculated as the sum of its approach spillbacks. For example, if two approaches to an intersection have spillback during the same time interval, the intersection is considered to have two spillbacks for that time interval. Occurrences of spillbacks are tracked and summarized for each approach and intersection in terms of frequency (e.g., 15 spillbacks on Approach A on a specific day).

Duration. Bottleneck duration measures how much time the bottleneck was active. For an approach, the duration of a bottleneck is the time elapsed between the bottleneck start and end on that approach. The duration of an intersection bottleneck is the period during which any of its approaches is congested.

Average Confidence Score. Each INRIX speed data record contains a confidence score value representing the data quality. Score 30 represents real-time data; Score 20 indicates historical average data; and Score 10 is used for reference speed. For each approach bottleneck, an average confidence score is calculated across all its constituent segments and time intervals and presented as a measure of data quality. Similarly, for an intersection bottleneck, an average confidence score is calculated across all its constituent segments and timestamps. It should be noted that some of the approaches at this intersection may not have had a bottleneck during this time period. Therefore, the average confidence score for an intersection bottleneck cannot be directly compared to the average confidence scores of its constituent approach bottlenecks.

Development of Visualization Tool

All the performance measures calculated in Step 4 were summarized into various tables and visualizations, including data tables, maps, heatmaps, and cumulative distribution functions (CDFs). Together they characterize the four industry-recognized dimensions of bottlenecks: duration, intensity (delay, number of bottlenecks, VMT, etc.), variability, and extent (queue length, spillbacks).

Variability was depicted through CDFs, heatmaps, and maps for any of the intensity measures. CDFs have been effectively used in many studies to characterize day-to-day variations in congestion (Institute for Transportation Research and Education, 2013). With the use of this concept, traffic delays at intersection bottlenecks were investigated using CDFs to characterize and communicate the variability of bottleneck intensity across days, time of day, and approaches. CDFs show the cumulative probability of a selected measure being less than or equal to a certain value. The cumulative probability from 0% to 100% is depicted on the Y-axis. The value of the measure is depicted on the X-axis. Changes in the shape of CDFs illustrate the day-to-day and intra-day changes of the performance measure. Between two CDF curves on the same graph, a more vertical curve is less variant and more reliable than another curve that is slanted. Heatmaps also characterize the intensity and the variability dimensions for the measure chosen (across date and time of day; day of week and time of day) for both the intersections and the individual approaches.

Figure 9 shows a dashboard from the visualization tool that captures a number of specific visualizations, which are zoomed in further in later figures. The dashboard includes the intersection bottleneck ranking table (Figure 10), approach bottleneck ranking table (Figure 11), CDFs (Figure 12), heatmaps for intersections and approaches (Figure 13), and a map view (Figure 14). The visualization tool shows both summaries and detailed results. The details of the tables and the graphs on the dashboard are provided on individual sheets. Users can customize the results in the visualization tool by determining several input parameters including the following:

- start and end analyses dates, days of week, and time-of-day periods
- number of intersections to be included in the ranking list
- intersections of interest by type, corridor, city or county, and data completeness on the intersection approach and by selection of specific intersection(s) displayed on the map
- performance measures for bottleneck ranking, heatmaps, and CDFs.

In addition to the summed and averaged measures, such as total delay and average duration, a number of normalization factors were used, including number of days, VMT, and length of roadway. The magnitudes of individual performance measures were used to select reasonable units in the visualization tool. For example VMT was often very large in magnitude, prompting the use of thousands of miles as the units. Although total delay was presented in vehicle-hours, the corresponding delay per vehicle-mile was often very small in magnitude, prompting the use of minutes per vehicle-mile as units. To provide context, intersection and approach characteristics such as length, AADT, length-weighted PSL, XD segment availability, AADT availability, and average XD speed data quality were presented along with the calculated performance measures. A weighted AADT was presented for intersections as a surrogate measure for intersection entering volume. It was calculated as the sum of the segment-length–weighted AADTs on all of its approaches.

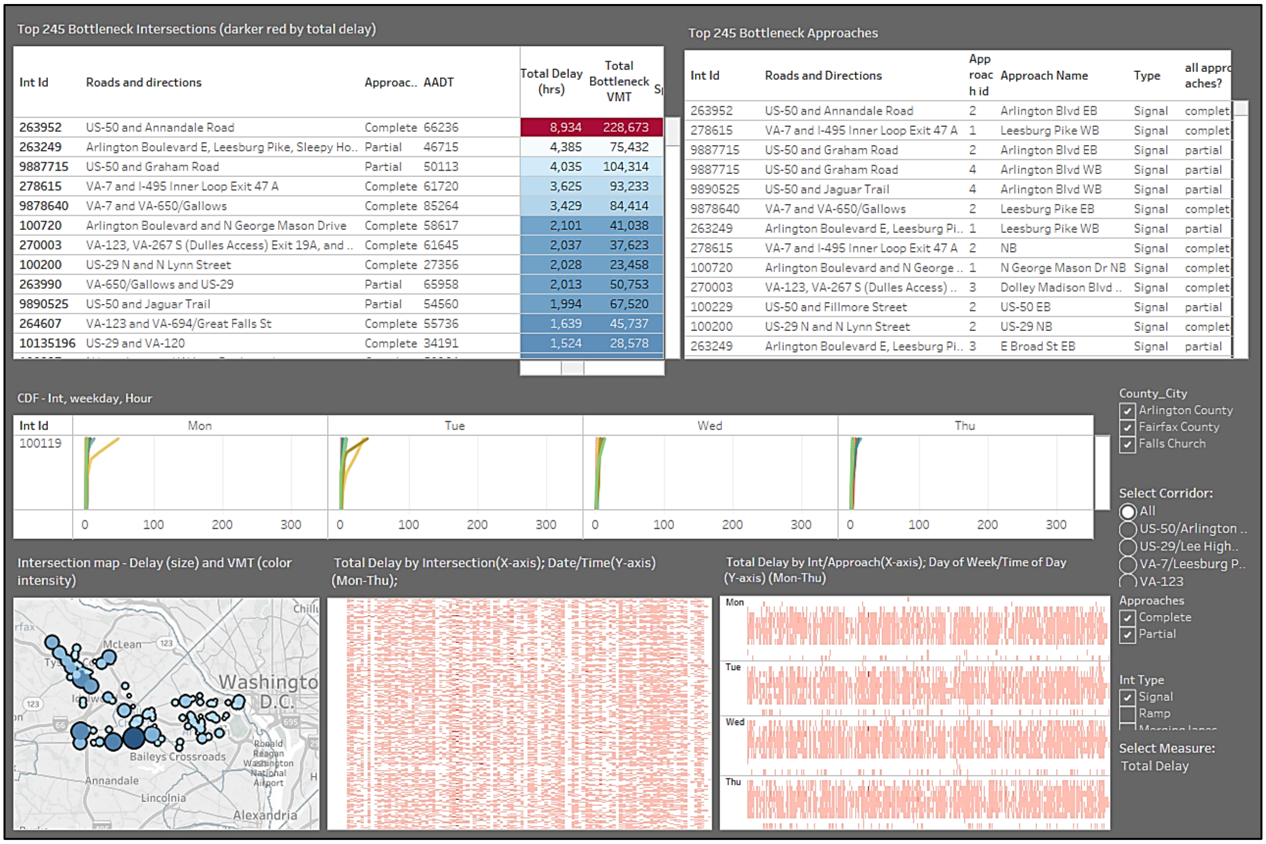


Figure 9. Dashboard of Visualization Tool. The dashboard includes Intersection Bottleneck Rank Table (top left), Approach Bottleneck Rank Table (top right), Cumulative Distribution Functions (CDFs) (center), Map view (bottom left), Intersection Delay Heatmap (bottom center), and Approach Delay Heatmap (bottom right).

Int Id	Roads and directions	Approac..	AADT	Avg. CS	# of Days	# of Bottlenecks	Total Duration (hrs.)	Total Delay (hrs)	Total Bottleneck VMT	Total Spillbacks	Avg. Max. Q len (mi)
263952	US-50 and Annandale Road	Complete	66236	28.6	44	109	223	9,645	264,004	916	0.96
9878640	VA-7 and VA-650/Gallows	Complete	85264	29.5	44	148	330	9,340	188,614	1,567	0.50
264588	VA-7 and VA-694/Lewinsville Rd.	Complete	59345	29.8	44	80	258	6,633	161,238	543	1.01
263990	VA-650/Gallows and US-29	Partial	65958	29.7	44	177	190	6,567	164,301	729	0.97
263249	Arlington Boulevard E, Leesburg Pi..	Partial	46715	24.2	44	71	385	6,430	102,086	1,367	0.70
264607	VA-123 and VA-694/Great Falls St	Complete	55736	29.7	44	109	237	6,257	156,271	1,441	1.01
9887715	US-50 and Graham Road	Partial	50113	29.8	43	163	173	6,038	182,453	255	0.79
279503	VA-7 and West Street	Complete	31754	27.6	44	111	218	5,072	85,794	157	0.55
9875627	VA-7, Westpark Drive, and Gosnell..	Partial	61240	30.0	44	155	117	4,891	108,707	590	0.49
264464	VA-7 and Spring Hill Rd	Partial	61569	29.9	44	118	124	4,685	101,021	622	0.39
278622	VA-7 and VA-123 E Off Ramp	Complete	67695	28.9	43	139	146	3,628	62,222	236	0.32
724755	VA-650/Gallows and US-50 Off Ra..	Partial	46517	28.1	44	157	281	2,835	59,077	747	0.40
264646	VA-7 and VA-695/Idylwood Rd	Partial	39452	29.8	44	170	142	2,755	89,181	236	0.38
708306	VA-7 and VA-267 E Exit 16A	Complete	61221	27.7	43	90	108	2,732	59,672	171	0.29
278615	VA-7 and I-495 Inner Loop Exit 47 A	Complete	61720	29.0	44	164	166	2,515	68,862	623	0.45

Figure 10. Snippet of Intersection Bottleneck Rank Table. This table lists the most congested intersections. The colors indicate the amount of delays caused by bottlenecks, with red representing the most delay and blue representing the least delay.

Int Id	Roads and Directions	.	Approach Name	Type	all approaches?	AADT	Avg. CS	# of Days	# of Bottlenecks	Total Duration (hrs.)	Total Delay (h..	Total Spillbacks	Avg. Max. Q Length ..	Total VMT (1000's)	Avg. Duration per day..
263952	US-50 and Annandale Road	2	Arlington Blvd EB	Signal	complete	25392	30.0	44	84	187.50	136.67	283	0.83	206.97	4.26
278615	VA-7 and I-495 Inner Loop Exit 47 A	1	Leesburg Pike WB	Signal	complete	20390	29.4	44	107	74.25	35.63	27	0.55	54.37	1.69
9887715	US-50 and Graham Road	2	Arlington Blvd EB	Signal	partial	25277	30.0	38	82	55.50	34.61	222	0.70	54.54	1.46
9887715	US-50 and Graham Road	4	Arlington Blvd WB	Signal	partial	24836	29.8	44	107	73.25	32.63	1	0.45	49.77	1.66
9890525	US-50 and Jaguar Trail	4	Arlington Blvd WB	Signal	partial	24901	29.8	43	77	65.50	31.93	262	0.70	64.07	1.52
9878640	VA-7 and VA-650/Gallows	2	Leesburg Pike EB	Signal	complete	32145	29.6	44	207	114.75	26.53	16	0.19	37.34	2.61
263249	Arlington Boulevard E, Leesburg Pi..	1	Leesburg Pike WB	Signal	partial	16888	29.7	43	118	59.25	22.35	237	0.50	28.15	1.38
278615	VA-7 and I-495 Inner Loop Exit 47 A	2	NB	Signal	complete	20213	28.9	30	59	76.75	22.03	307	0.39	34.03	2.56
100720	Arlington Boulevard and N George ..	1	N George Mason Dr NB	Signal	complete	12650	29.2	43	65	43.25	20.71	173	0.78	24.44	1.01
270003	VA-123, VA-267 S (Dulles Access) ..	3	Dolley Madison Blvd ..	Signal	complete	23160	29.5	44	98	98.25	19.73	232	0.15	20.22	2.23
100229	US-50 and Fillmore Street	2	US-50 EB	Signal	partial	26840	30.0	44	67	58.25	19.33	233	0.52	45.83	1.32
100200	US-29 N and N Lynn Street	2	US-29 NB	Signal	complete	7379	29.8	44	136	119.75	19.28	51	0.20	12.66	2.72
263249	Arlington Boulevard E, Leesburg Pi..	3	E Broad St EB	Signal	partial	9621	27.8	44	210	205.50	16.19	45	0.14	12.61	4.67
13937878	N Glebe Road and Henderson Road	4	N Glebe Rd NB	Signal	partial	14033	29.9	44	112	60.75	15.78	39	0.32	15.43	1.38
100120	US-29 and VA-237	1	VA-237 NB/WB (Wash..	Signal	complete	12140	29.7	44	104	77.25	15.56	309	0.25	13.34	1.76
263997	VA-650/Gallows and VA-695/Idylw..	1	Gallows Rd NB	Signal	partial	15831	29.9	43	65	40.50	15.00	25	0.69	23.62	0.94

Figure 11. Snippet of Approach Bottleneck Rank Table. This table lists the most congested intersection approaches. The colors indicate the amount of delays caused by bottlenecks, with red representing the most delay and blue representing the least delay.

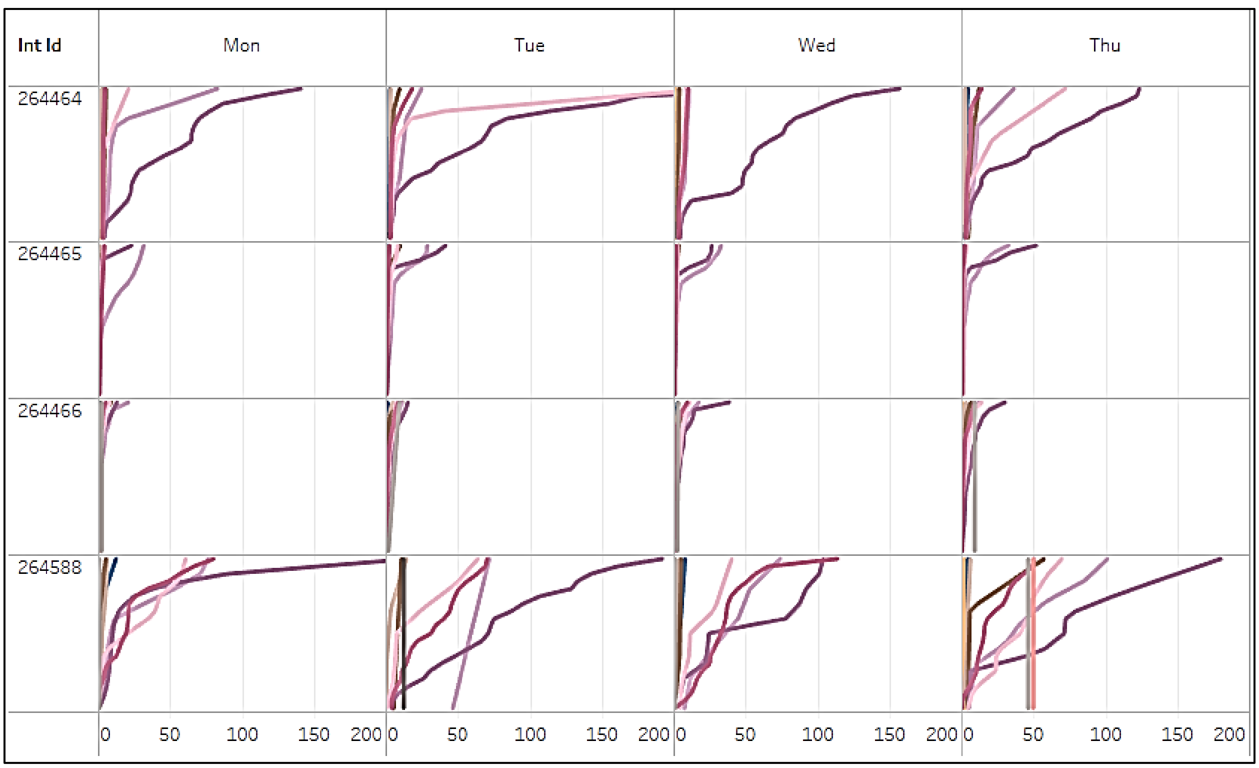


Figure 12. Snippet of Vehicle-Hours of Delay Cumulative Distribution Function (CDF). The CDFs illustrate the variability of bottleneck intensity across days, time of day, and intersections; the line color indicates the hour of day.

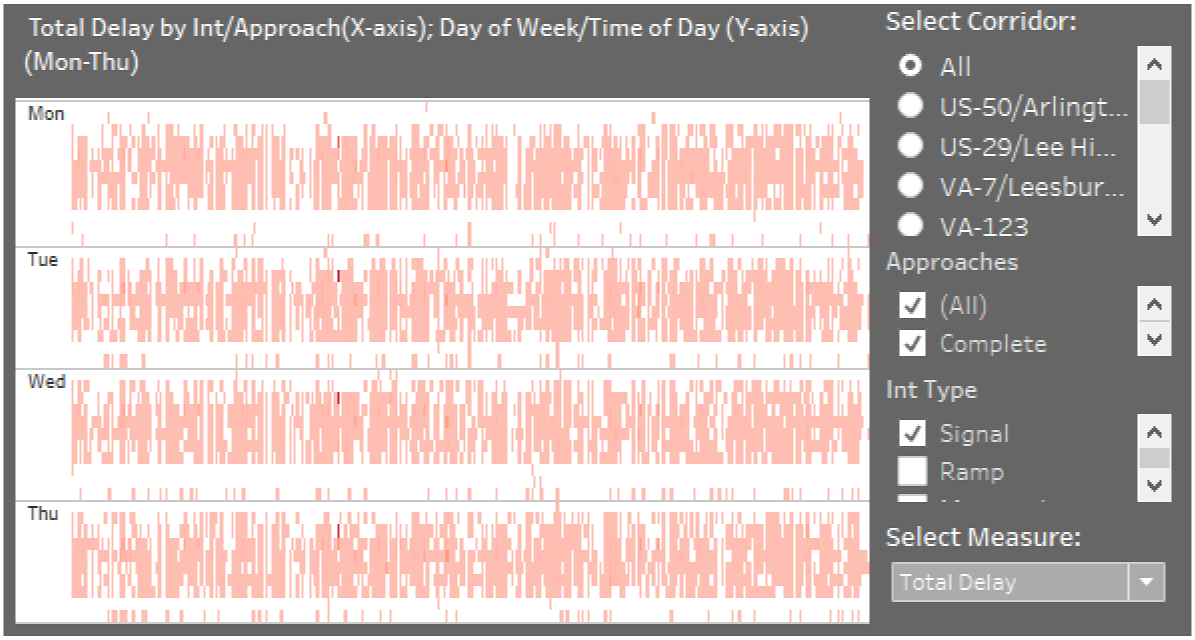


Figure 13. Example Intersection Delay Heatmap (left) and Dashboard Input Options (right). Day of Week and Time of Day (12 A.M. to 11 P.M. top to bottom) on Y-axis of the heatmap; Approach IDs on X-axis of the heatmap.

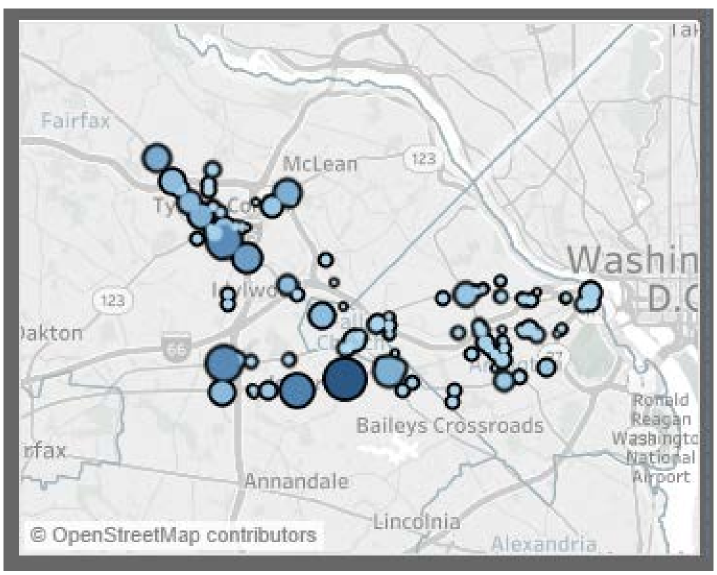


Figure 14. Map Showing Intersections With Delay and Vehicle Miles Traveled (VMT). The size of the dots indicates the amount of delays; the color intensity indicates the amount of VMT, with dark color representing the most delay.

Spatial maps are particularly useful to characterize the extent and intensity through the selected measures. By default, the delay measure was selected to represent the size of the dot, and VMT was selected to represent the color intensity. However, the second measure can be modified by the user. A matrix of maps was also used to characterize effectively the variability of these measures across different days of the week and times of the day (Figure 15).

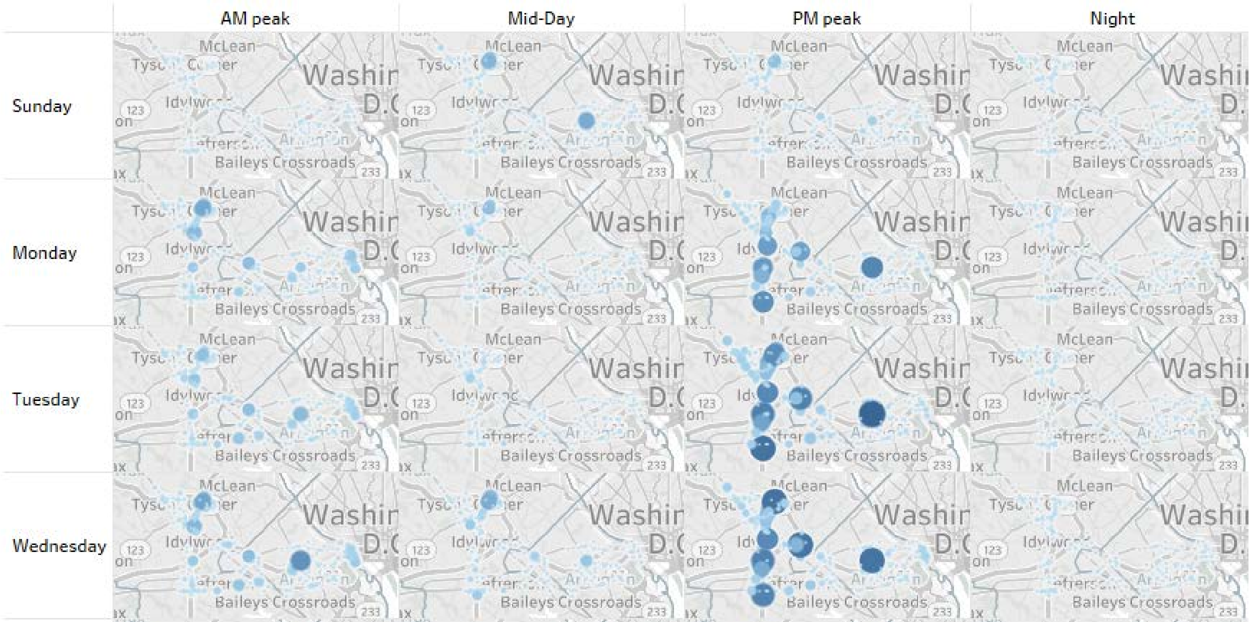


Figure 15. Matrix of Maps Showing Intersection Delay (Size) and Vehicle Miles Traveled (Color Intensity) by Day of Week (X-axis) and Time of Day (Y-axis)

Task 3: Study Network Identification, Data Preparation, and Methodology Application

Identified Study Network

The TRP, advisory panel, and research team identified some guiding principles to select the case study network, such as diversity of characteristics including speed limits and volumes. The specific network selected using these principles for this study was an urban network in Northern Virginia with 107 signalized and 138 unsignalized intersections. The intersections and approaches are shown in Figure 16.

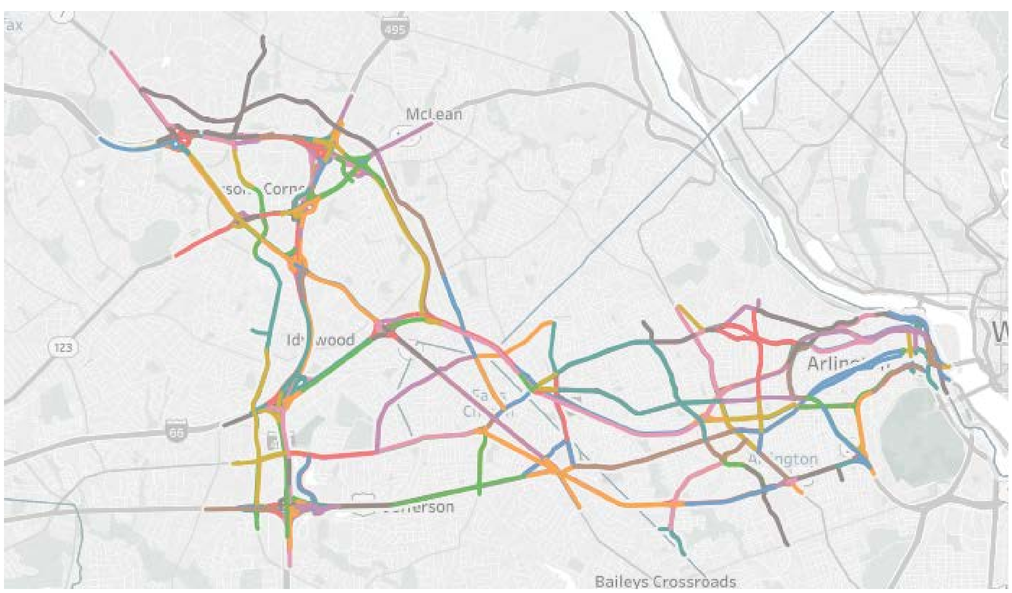


Figure 16. Study Network in Northern Virginia. Each color represents one intersection.

Prepared Data

This study used high spatial resolution probe speed data based on the INRIX XD reference system. INRIX XD data provide increased granularity for queue detection with shorter segmentation than TMC data and have better coverage on arterial roads, as shown in Figure 17. The study network contains 1,096 XD segments.

INRIX XD data for the period October 1, 2017, to June 30, 2018, were used in this case study. Traffic speeds and associated confidence scores were aggregated to 15-minute intervals. The raw XD data consisted of individual data files (.csv format) for each segment. Geographic Information System (GIS) shapefiles of the XD network were used to retrieve the reference speeds and segment locations and lengths. The shapefiles were also used to identify the XD segments associated with each intersection approach and their order in the travel direction. Table 2 gives an example of some intersections and their associated XD segments, extracted from various GIS data. INRIX updates its underlying network regularly, and these changes in segment definitions within iPeMS caused some difficulties in data conflation. Because of the lack of sophisticated tools and the complexity from the novel approach, the conflation process required a large amount of manual processing and was time-consuming.

Figure 17. INRIX XD and TMC Coverages in Northern Virginia. TMC = traffic management channel; gray line = XD segments; orange line = TMC segments.

Table 2. Example of Intersections and Associated XD Segments Data

Intersection ID	XD1 (North)	XD2 (East)	XD3 (South)	XD4 (West)	No. of Missing XDs	Names of Roads and Direction	Latitude	Longitude
100739	1310287299	1310319805	1310498832		0	Arlington Blvd E and N Carlin Springs Rd		
101192	1310512302		1310476118	1310285288	0	Arlington Blvd W and N Carlin Springs Rd		
101176	1310460597	1310302610	1310380224		0	S Carlin Springs Rd and Glen Carolyn Rd		
100832	1310589572	1310383853	1310273257	1310423575	0	Wilson Blvd and N George Mason Dr		
100469	1310544098	1310431074	1310398505	1310479278	0	VA-237 and N George Mason Dr		
279504	1310251929	1310298248	1310596703		1	US-29 and Annandale Rd		
N1		1310531021	1310356600	1310356844	0	Tysons Corner Center	38.91952	-77.2221

Red shading indicates a physical approach exists without a defined XD segment; blue shading indicates no physical approach exists.

Traffic volume data (AADT) for the same period and PSLs were obtained in GIS shapefiles and in spreadsheets from a number of sources including the VDOT Traffic Count Program, the VDOT GIS, and Arlington County GIS Open Data. The roadway segmentations and the underlying linear referencing systems in these GIS networks were different from the INRIX segmentation, and the XD segments were usually shorter than the VDOT segments. The INRIX XD network was used as the base network for this study. A length-weighted average AADT was calculated when an XD segment crossed multiple VDOT segments. Because 15-minute volumes were not available for most XD segments, AADT and typical national average volume profiles were used to estimate the traffic volume on each XD segment during each time interval (Schrank et al., 2012).

Both traffic speed and volume data were assessed for conformance with known theoretical and practical bounds. Missing speed data were replaced with historical average speeds based on segment, month, day of week, and hour. AADTs were missing for 187 of the total 1,096 XD segments, and most of these segments were freeway ramps. The missing AADTs for arterial segments were replaced by the AADT for the nearest segment with similar traffic conditions, and for ramps, the AADTs were replaced with an average ramp traffic volume in the study area of about 5,000. Probe speed data were then conflated with volumes, PSL data, and reference speed data. Table 3 shows an example of the combined data. Each row describes the condition of an XD segment during a 15-minute interval, including the speed, quality of speed data, volume, downstream intersection ID, approach ID, order on the approach, segment length, and INRIX reference speed for the XD segment.

Programming and Computation

In accordance with the calculation procedures shown in Figure 8, two Python programs were developed, one for each Method (I and II), to identify bottlenecks and to calculate performance measures. The computing was performed on the high performance cluster at the University of Virginia. One standard node from the cluster including 20 cores with 12 GB memory per core was used. The computing time for Method II (6 hours) was about 6 times that for Method I (1 hour) because of the loop structure to evaluate congestion at each segment; Method II used 62 GB memory per core. The outputs included the calculated performance measures discussed in Task 2 and were imported to the visualization tool for further analysis.

Three sets of threshold speeds were used in the computations:

1. 60% of PSL
2. 60% of INRIX reference speed
3. 60% of LTS.

All three threshold speeds have different strengths and weaknesses. It may be easier to communicate delay calculated with respect to PSL with the public and elected officials, but average speeds on arterials are often lower than the PSL because of traffic control devices and turning movements at intersections. INRIX reference speed was unexpectedly low (e.g., 5 mph) for some segments. LTS was calculated using INRIX data during 10 P.M. to 5 A.M., but the probe penetration rates are lower during these periods and could result in less real-time data.

Table 3. Example of Combined Dataset

Date and Time	Speed (mph)	Confidence Score	Volume (vehicles)	XD	Intersection ID	Approach	Order	Length (miles)	Reference Speed (mph)
10/1/2017 0:00	40	30	145	1310216620	100079	2	1	0.125	41.44
10/1/2017 0:15	40	30	133	1310216620	100079	2	1	0.125	41.44
10/1/2017 0:30	41	30	119	1310216620	100079	2	1	0.125	41.44
10/1/2017 0:45	41	30	107	1310216620	100079	2	1	0.125	41.44
10/1/2017 1:00	42	30	98	1310216620	100079	2	1	0.125	41.44
10/1/2017 1:15	42	20	90	1310216620	100079	2	1	0.125	41.44
10/1/2017 1:30	42	20	81	1310216620	100079	2	1	0.125	41.44
10/1/2017 1:45	42	30	72	1310216620	100079	2	1	0.125	41.44
10/1/2017 2:00	42	30	66	1310216620	100079	2	1	0.125	41.44
10/1/2017 2:15	41	10	58	1310216620	100079	2	1	0.125	41.44

Figure 18 compares the three threshold speeds for all 1,096 XD segments. The LTS and INRIX reference speeds are consistent for most segments, as they are calculated from the same data source. PSL is significantly different from the other two speeds on some XD segments. Those segments tend to be short, usually less than 0.05 mile, and many of them are located at access points on the arterials.

The quality of probe data can affect the INRIX reference speed and LTS. To evaluate the quality of XD data, the average confidence score was calculated for all segments. The LTS shown in Figure 18 was calculated with real-time data only. In Figure 18, the segments are sorted in ascending order based first on PSL, second on INRIX reference speed, and third on LTS. Although the latter two often trend together, they both differ considerably from the PSL. Such differences are quite common on congested arterials and on ramp segments.

Figure 19 shows the LTSs calculated with real-time data (score = 30) and with all data available (score = 10, 20, or 30). The differences between the two sets of LTSs are within 0.5 mph for almost 40% of the XD segments. The study area is located in a very busy urban road network, and probe penetration rates are expected to be higher, which indicates better data quality. These results may not be transferable to more rural areas however.

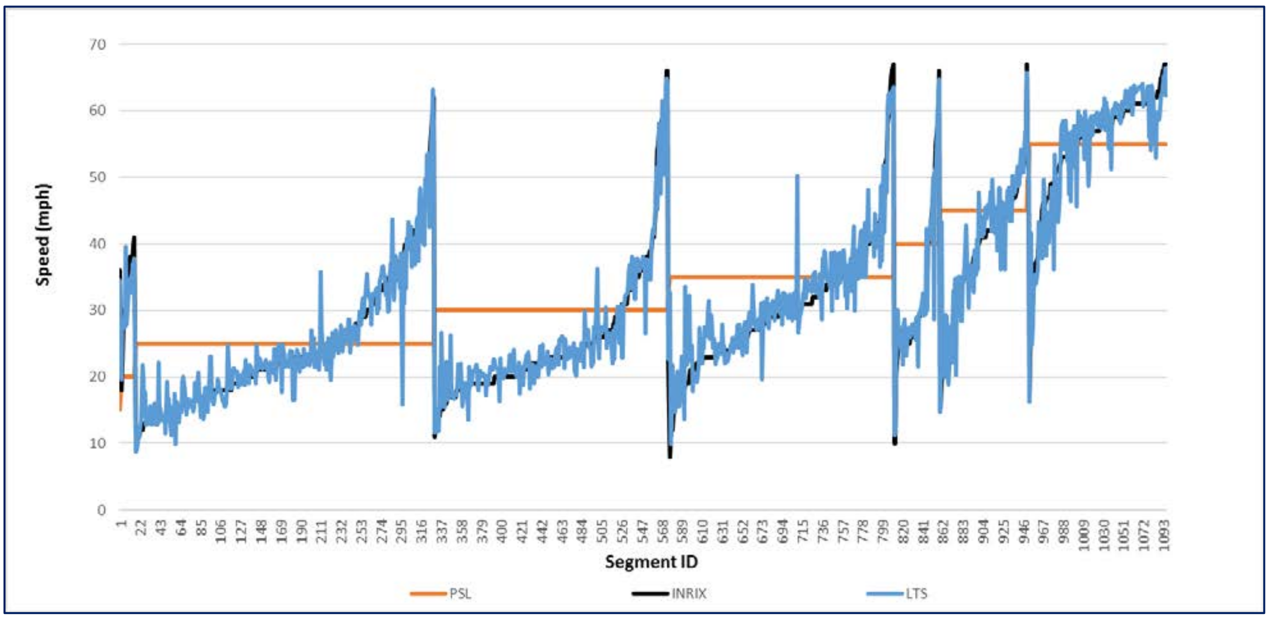


Figure 18. Posted Speed Limit (PSL), INRIX Reference Speed (INRIX), and Light Traffic Speed (LTS) for Studied Segments

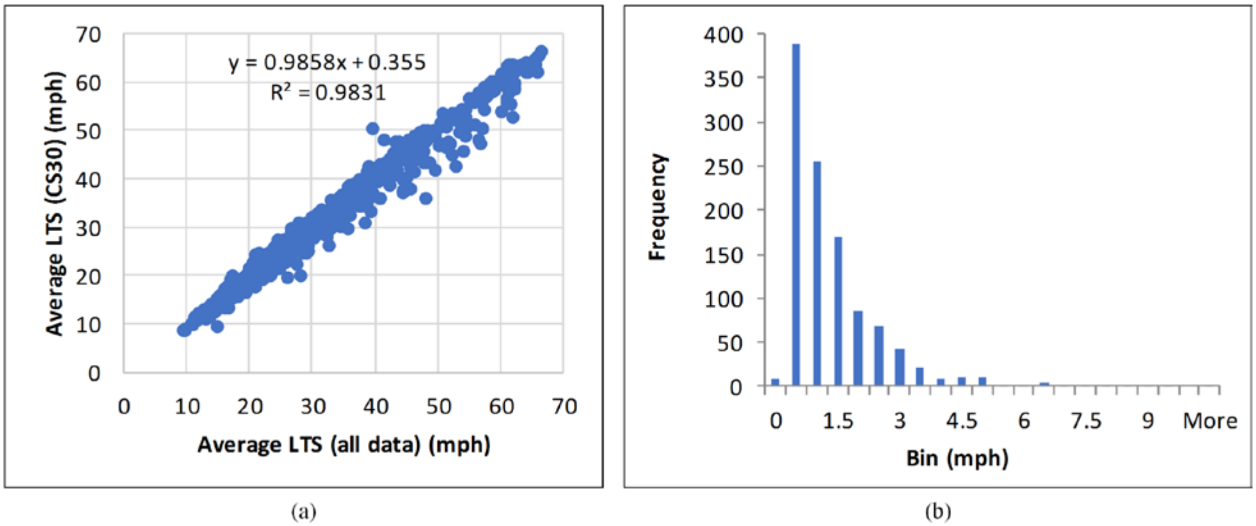


Figure 19. Comparison of Light Traffic Speed (LTS) Calculated From Score 30 (CS30) Data and All Data Using (a) Scatter Plots and (b) Histogram of Absolute Differences

Task 4: Analysis of Case Study Results

Findings from the sensitivity analyses are presented first, and trends and analyses are presented second. These findings were used to narrow down the results for further analyses and validation.

Sensitivity of Results to Threshold Speeds

Results from the three threshold speeds were in line with their known strengths and weaknesses. It may be easier to communicate delay calculated with respect to PSL with the public and elected officials, but average speeds on arterials are often lower than the PSL because of traffic control devices and turning movements at intersections. On many segments, PSLs were quite high compared to the actual traffic speeds, resulting in those segments being judged as continually congested irrespective of the queue calculation method. The most congested segments had congestion with respect to PSL for the entire 9-month period of analysis. For this reason, PSL was not studied further.

On the other extreme, since some segments were marked with very low INRIX reference speeds such as 2 mph to 10 mph, they were never reported as congested with respect to INRIX reference speed during the entire period. Although it is possible that some segments are rarely congested, a lack of variance in the congestion conditions renders the algorithm outputs unusable for project prioritization and funding purposes. The LTS provided a middle ground between the other two threshold speeds and was therefore studied in great detail. However, the quality of the probe data on segments with low probe penetration rates can affect the LTS, as the LTS is calculated using INRIX data from 10 P.M. to 5 A.M. when the probe density is often low, especially on rural and low volume roads.

Sensitivity of Results to Queue Calculation Method

Table 4 shows the top 15 signalized intersections with the highest total delays using Method I and the total delays for the same intersections using Method II for the morning period (5 A.M. to 11 A.M.) on typical weekdays (Monday through Thursday) between April 1, 2018, and June 15, 2018. In line with the expectations, the Method I delays were always equal to or higher than the Method II delays. For most intersections in this list, the ranks from both methods were similar even though the actual delay values were sometimes different. Figure 20(a) gives a comparison of the ranks of the same intersection in the two methods, where the x-axis is the rank in Method I and the y-axis is the rank in Method II. The ranks in Method I and Method II were highly correlated, with a Pearson correlation coefficient of 0.962. Although 10 of the 107 intersections ranked the same in Methods I and II and the ranks in both methods look similar for many intersections in Figure 20, a Wilcoxon rank test found that the difference between the ranks in Methods I and II was statistically significant, with a *p*-value of 0.048. For those intersections with higher ranks in Method I but lower ranks in Method II, either congestion was more likely to occur near the middle of the approach or the first XD segment on the approach was too short to reflect the real traffic condition on the entire approach. Given these observations and that the computing time for Method II was about 5 times that for Method I, Method I was deemed more suitable for a quick screening and was therefore used for the remainder of the analyses and for validation.

The top intersection by Method I was still ranked first by Method II. The biggest rank difference was for the last intersection, with Rank 15 by Method I and Rank 22 by Method II. One major approach at this intersection has two left-turn lanes. The XD segment closest to the intersection is very short (about 0.02 mile). It is possible that the delay because of left-turn spillback was not captured in Method II; this is discussed further in the validation section.

Table 4. Comparison of Results of Method I and Method II

Intersection	Weighted AADT	Method I		Method II		XD Complete?
		Rank	Delay (veh-hr)	Rank	Delay (veh-hr)	
US-50 and Annandale Rd	66236	1	8934	1	8323	Yes
Arlington Blvd E and Sleepy Hollow Rd	45960	2	4385	3	2658	No
US-50 and Graham Rd	50376	3	4035	2	3953	No
VA-7 and I-495 Inner Loop Exit 47 A	61585	4	3625	4	2435	Yes
VA-7 and VA-650/Gallows	85179	5	3429	6	2053	Yes
Arlington Blvd and N George Mason Dr	57065	6	2101	5	2093	Yes
VA-123, VA-267 S, and Anderson Rd	61815	7	2037	9	1956	Yes
US-29 N and N Lynn St	28085	8	2028	10	1827	Yes
VA-650/Gallows and US-29	66109	9	2013	8	1971	No
US-50 and Jaguar Trail	55063	10	1994	7	1982	No
VA-123 and VA-694/Great Falls St	54393	11	1639	15	1100	Yes
US-29 and VA-120	33981	12	1524	11	1461	Yes
N Lynn Ln and Wilson Blvd	50565	13	1469	13	1196	Yes
VA-684 and VA-694/Great Falls St	23020	14	1417	18	963	Yes
VA-650/Gallows and US-50 Off Ramps	46369	15	1328	22	814	No

AADT = annual average daily traffic. The “XD Complete?” column indicates if all approaches are covered in the INRIX XD network.

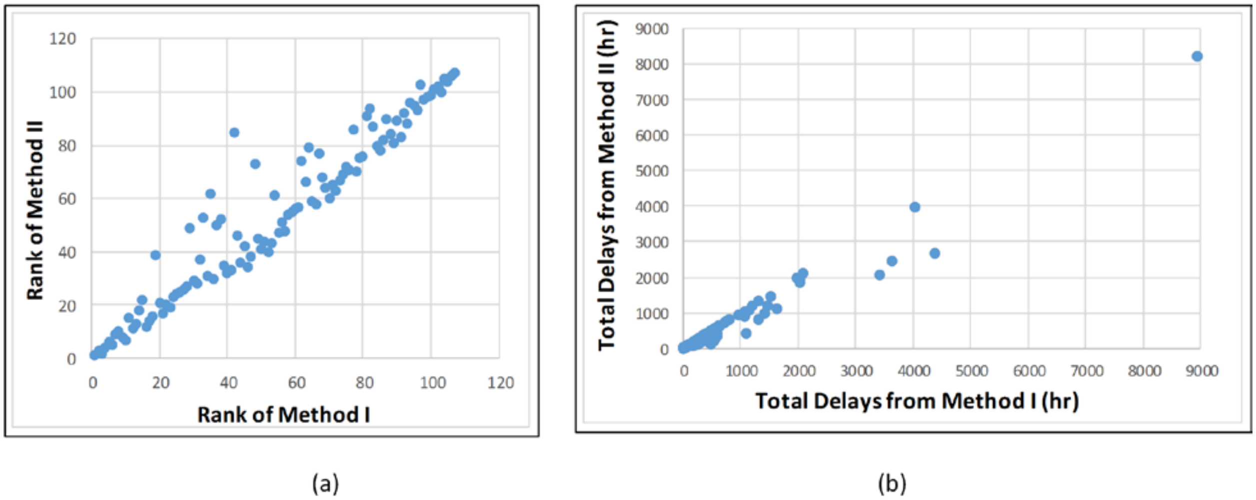


Figure 20. Comparison of Results From Methods I and II for Signalized Intersections: (a) ranks by delays; (b) total delays

As discussed in the "Methods" section, Method I calculates the delays on the entire approach ending at an upstream intersection, which will likely make the intersections with closely spaced access points on approaches rank higher. Although the identified bottleneck in such a case is not related to the intersection itself, it would identify problems with access control. Again, delays calculated in Method I are always equal to or more than those calculated in Method II, as shown in Figure 20(b). The approaches with equal delays in both methods have only one XD segment on the approach or the first XD segment is always congested when any other segment on the approach is congested. Method II emphasizes the delay on the segments closest to the intersection center, which might underestimate the delay if the first segment on the approach (order = 1) is very short and/or the turning volumes are very high. Access density information for the study network was not readily available to conduct a causal analysis, and its collection was beyond the scope of this study.

The "XD complete?" column in Table 4 shows the completeness of the intersections. Wherever an approach is not covered in the INRIX XD network, the corresponding intersection is labeled as incomplete in Table 4. A total of 49 of the 107 signals in the study network were incomplete this way. The second and third intersections in Table 4 ranked high despite such incompleteness.

Trends and Anomalies

A number of major trends and anomalies were presented in the previous sub-sections on sensitivity analyses. Based on those findings, results from the LTS threshold and Method I were analyzed in significant detail and are presented in this section. As explained before, results from existing tools do not provide a direct correlation to the results of this study. Therefore, quantitative analyses and statistical tests could not be performed. The trends and anomalies were studied in detail to understand better the strengths and weaknesses of the methodology, data, and visualizations in comparison to the theoretical expectations and practical knowledge regarding the local traffic.

Time-of-Day Congestion Patterns

The average bottleneck delay by time of day for weekdays exhibited an expected trend across all 107 signalized intersections (see Figure 21). In this figure, the X-axis represents time of day and the Y-axis represents individual intersections. The presence of congestion during any 15-minute period was coded as 0.25, and the absence was coded as 0. Therefore, the average congestion of 0.5 for an hour in the entire dataset means that on average 30 minutes was congested for that hour in the analysis period. It can be seen that most intersections had congestion either in the A.M. peak period or P.M. peak period or both. Some intersections had little congestion at any time of the day, whereas a few had congestion for most of the daytime. A few infrequent congestion spots were seen during nights at some of the intersections. A similar study of the weekends showed that most intersections had little congestion at any point whereas a few had several hours of congestion.

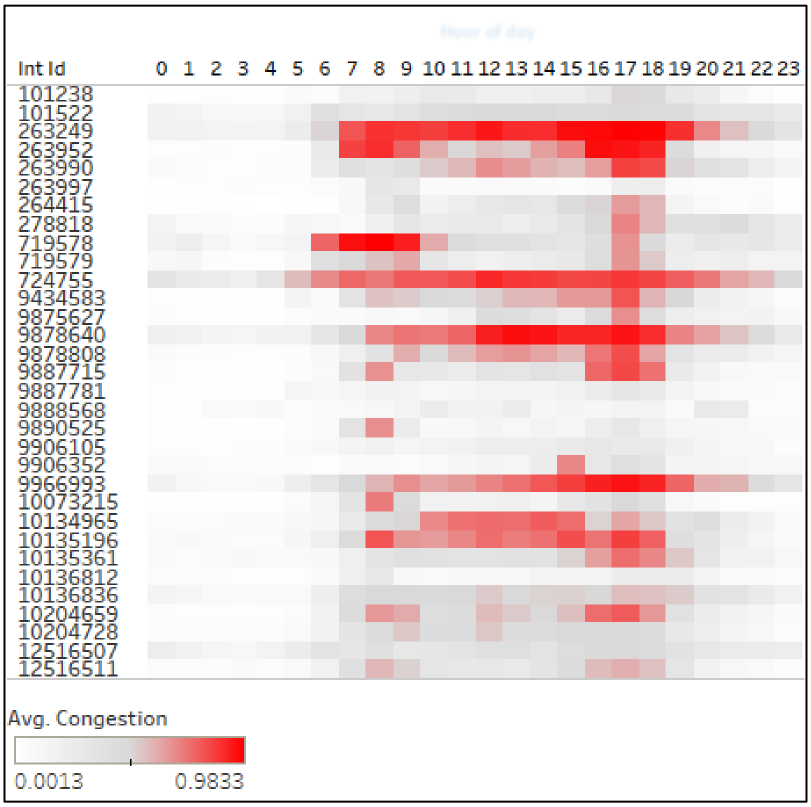


Figure 21. Average Weekday Congestion by Time of Day for Select Intersections. The Intersection ID is on the Y-axis, and the Time of Day is on the X-axis. Each hour was analyzed by 15-minute block with 0 = no congestion within the 15 minutes and 0.25 = congestion presence within the 15 minutes; an average value was calculated for each hour. An average congestion of 0.5 for an hour means that on average 30 minutes within that hour was congested in the analysis period.

Time Gaps Between Bottlenecks

The time gaps between subsequent bottlenecks at each intersection and approach were analyzed in detail; one example is shown in Figure 22, which covers the entire analysis period of 9 months from October 1, 2017, through June 30, 2018 (i.e., for a total of approximately $9 \times 30 = 270$ days).

Each color line represents a specific signalized intersection. The X-axis and the Y-axis, respectively, represent the time gap between successive bottlenecks at that intersection (i.e., time between the end of one bottleneck and the start of the next) and the number of times a specific gap was observed in the analysis period. Given that the input traffic speed and volume data were aggregated at 15 minutes, the minimum possible gap was also 15 minutes. The X-axis bins were 15 minutes each, and all gaps at or above 420 minutes (i.e., 7 hours) were combined. The value of 420 minutes was selected as the upper bound as road segments and intersections were expected to have low nighttime traffic for the 7 hours between 10 P.M. and 5 A.M. Intersections can legitimately have fewer than 270 gaps of 420+ minutes for reasons such as congestion in the overnight periods or long gaps because of no congestion during the weekend, etc.

At many intersections, the minimum 15-minute gap was observed on many occasions. Several valid field causes exist for such small gaps including the signal's cycle length and its relationship to the start of the 15-minute analysis period, probe data sample sizes, and turn-lane geometry and traffic demand. The number of bottlenecks is also sensitive to the analysis time interval. Because of these observations, the number of bottlenecks was not deemed a useful measure or normalization parameter to other measures such as delay in this study. Future studies could analyze patterns in the bottleneck durations and gaps to identify specific congestion causes such as poor progression, perhaps because of a school speed zone or pedestrian activity.

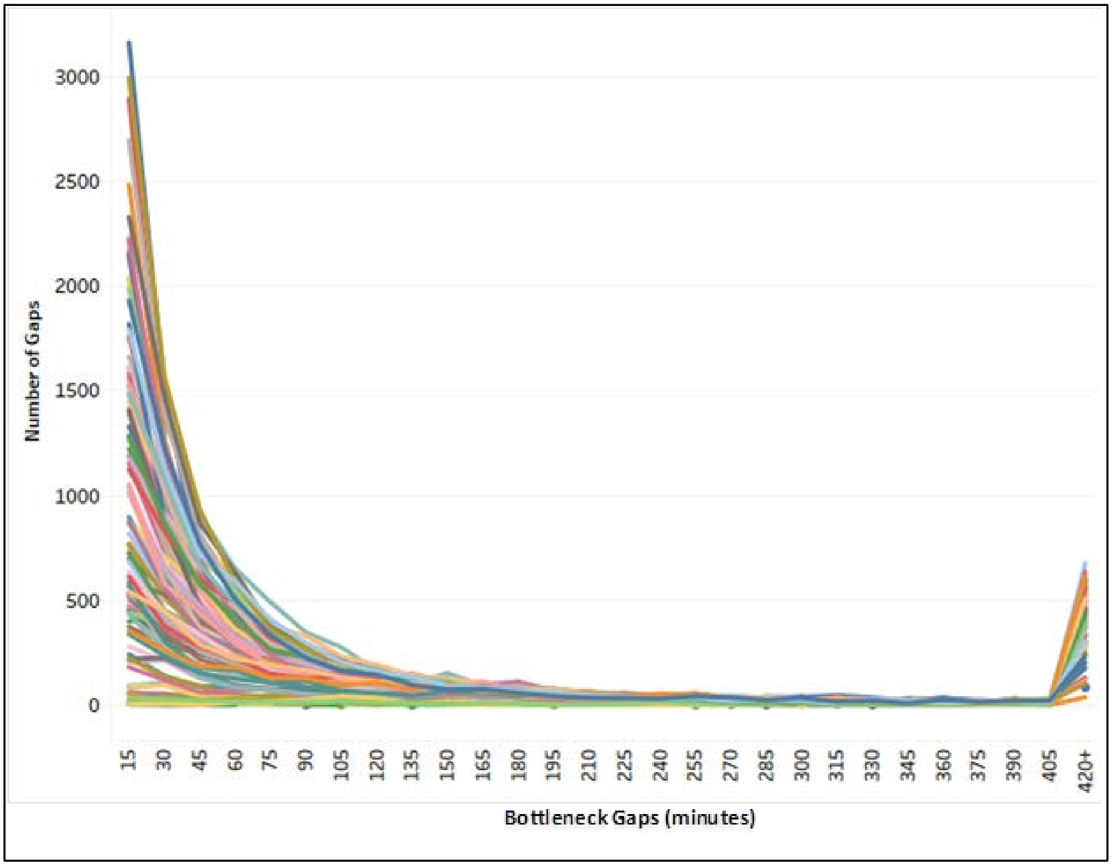


Figure 22. Frequency of Bottleneck Gaps by Intersection. Each color line is one intersection.

Temporal Patterns of Performance Measures

Figure 23 shows an example of the trends of four performance measures from day to day and by the start hour of the bottleneck for one specific intersection in Fairfax County. The trends for the other 46 intersections in the same county are visible in the background in some graphs. Figures 23(a) and (b), respectively, present the total bottleneck delay and the total bottleneck VMT. Figures 23(c) and (d), respectively, present the total bottleneck delay by VMT and the total bottleneck delay by length in miles of all approaches. Even though by design the base demand volume and the VMT for any given XD segment follow a strictly cyclical pattern by day of week and time of day, the bottleneck VMT and the other measures depend on actual speed values for that specific date and time. Therefore, the four measures presented in Figure 23 follow an approximate cyclical pattern. For the 9-month analysis period, the weekday peaks and the weekend valleys are most prominent in Figures 23(a) and (b). Further, although total delay and VMT are quite high at this intersection in comparison to the other intersections analyzed, the normalized delay per VMT and the normalized delay per mile are quite smaller. Different use cases may need different performance measures; these specifics have to be identified by the practitioners after full field implementation of this methodology.

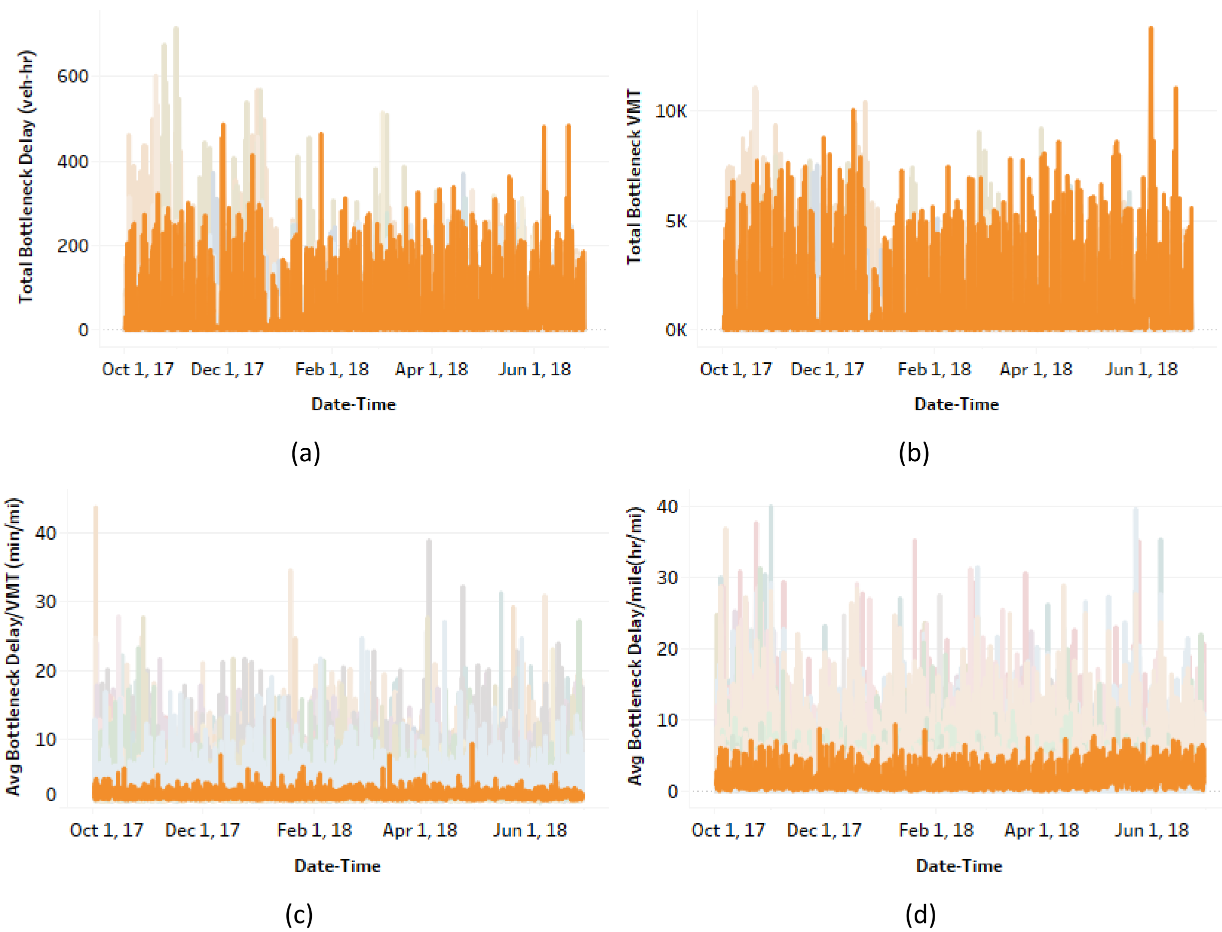


Figure 23. Example of Trends of Performance Measures by Date and Hour of Day for One Intersection in Fairfax County (Intersection 263952): (a) total intersection bottleneck delay (vehicle-hours); (b) total intersection bottleneck vehicle miles traveled (VMT); (c) average bottleneck delay per VMT (minutes/mile-traveled); (d) average bottleneck delay per mile of approach (hours/mile)

The distributions of different performance measures by hour of the day and intersection approach were also studied. An example of such distributions was presented in Figure 9. These results were not fully field verified in this study; however, they seemed reasonable and in line with the nominal expectations of higher bottleneck delays during peak hours and little to no delay during off peak hours. The differences in performance measures among different approaches of an intersection need to be field verified in a future study.

Figure 24 shows an example of the trends for day of week and time of day for the spatial extents of bottlenecks at intersections and approaches. The X-axis in these heatmaps shows individual intersections and intersection approaches sorted by ID number. It should be noted that the average maximum queue length is based on the starting time of the bottlenecks and the spillbacks are shown by each time of day. Some patterns can be readily observed based on the weekday peak periods. The white spaces in Figure 24(a) indicate the day of week, time of day, and intersection when bottlenecks never started during the analysis period. The spillbacks often bunched together along the columns, indicating that multiple approaches to the same intersection often have spillbacks together.

Across facility types, nodes on freeways often displayed the highest delays owing to the very high freeway mainline traffic volumes and relatively long distances between interchanges in comparison to the arterial signal intersections. When the two facility types were analyzed together, several top bottlenecks were invariably represented by freeway nodes. To understand arterial signal bottlenecks better, they needed to be isolated from the freeway bottleneck locations. Off ramp approaches often had the smallest delays owing to the short approach lengths and smaller traffic demand volumes in comparison to the mainline intersections.

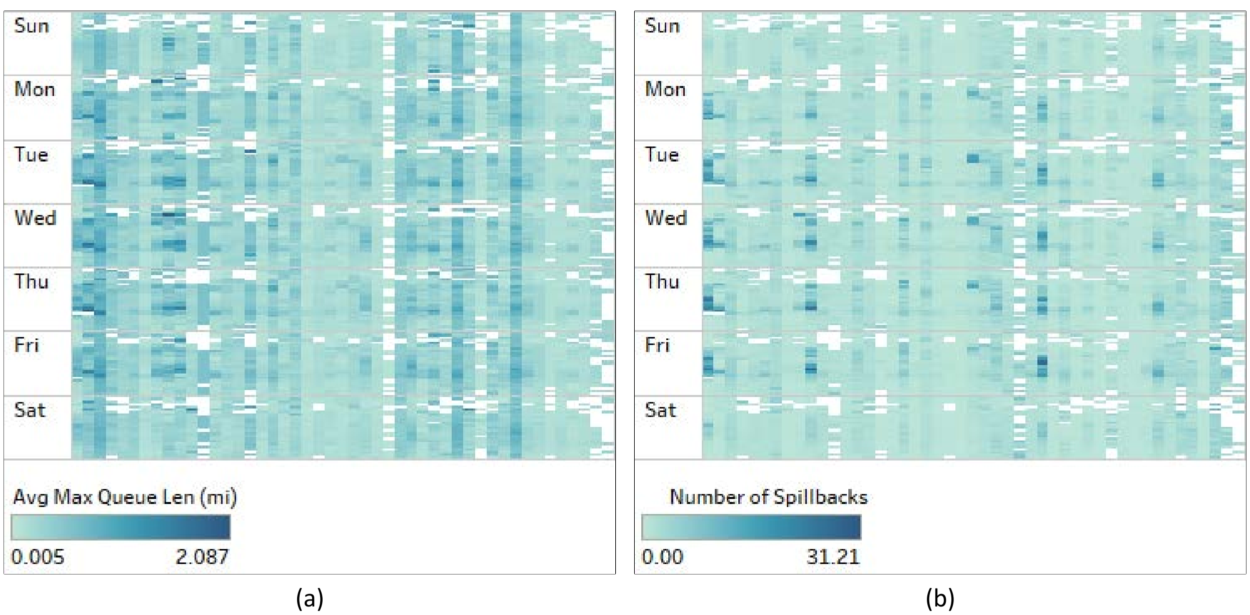


Figure 24. Example of Trends for Day of Week and Time of Day: (a) intersection bottlenecks by average maximum queue length (miles); (b) approach bottlenecks by number of spillbacks. The Y-axis on the heatmaps shows the day of week and time of day (12 A.M. to 11 P.M. top to bottom) within each day of week; the X-axis shows individual intersections in (a) and intersection approaches in (b) sorted by ID number.

Data Quality Impacts

Almost all intersection and approach bottlenecks during the weekday peak periods had high-quality speed data, with average confidence scores above 27 and 29, respectively. These observations indicated that low data quality is generally not affecting the approach and intersection results in the peak periods in any noticeable manner. However, a relative reduction in the average confidence scores from approaches to intersections was observed. As explained earlier, the intersection confidence score includes all the approaches to that intersection, irrespective of their congestion status, and the approach confidence score similarly includes all constituent segments, irrespective of their congestion status. Therefore, owing to insufficient probe samples, some uncongested approaches resulted in the default higher historic speed values. On the one hand, this observation in a highly urban area might pose some concerns for rural areas with lower traffic volumes and probe samples. On the other hand, (1) the magnitudes of the differences between the two average confidence scores were small; (2) in most situations, this assumption of free-flow traffic when probes are not available is reasonable; and (3) the focus of this study to identify highly bottlenecked locations may be little affected by such low probe sample concerns.

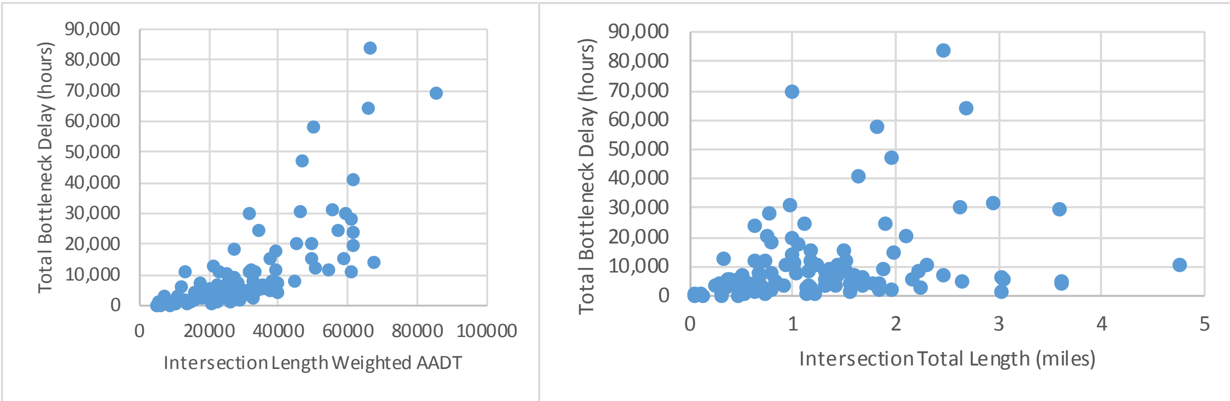
Overnight periods and weekends generally had relatively lower speed data quality than weekday peak periods, with some average confidence scores less than 20. However, most intersections and approaches still had average confidence scores above 25. Again, this observation is not surprising and is not expected to affect bottleneck identification in general.

Impacts of AADT and Approach Length on Measures

Figure 25(a) shows that higher AADTs were generally correlated with higher delays, in line with the conceptual and practical expectations. Figure 25(b) also shows an expected trend between delays and lengths. Shorter approach lengths generally lead to small delays, whereas longer approach lengths may lead to smaller or larger delays. However, as a consequence, when several closely spaced intersections all have congestion and delays together, all of them will individually have low delays and will rank low on the network bottleneck list. One potential approach identified during this study to mitigate this limitation is to define super nodes that study multiple closely spaced intersections together, similar to the research suggestion expressed earlier to study the various ramps at an interchange together as a super node.

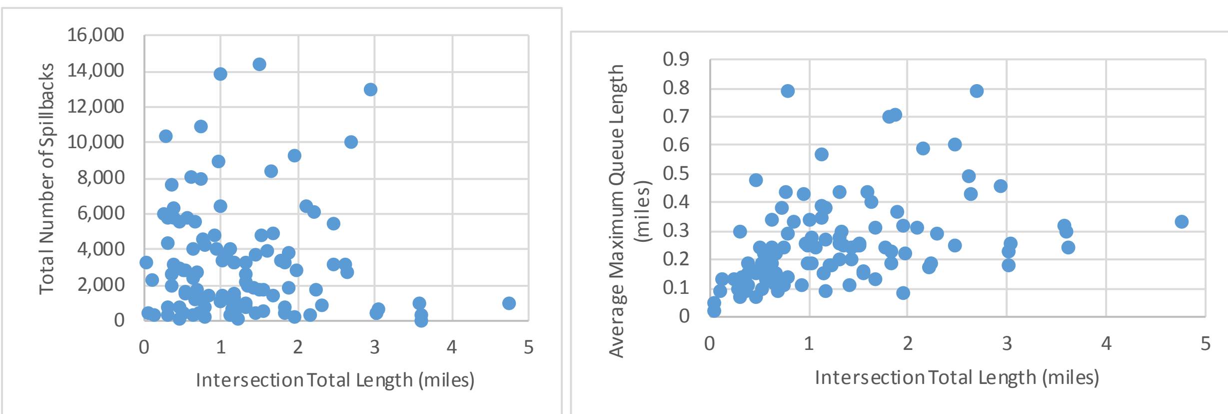
As expected, Figure 26 shows that the total number of spillbacks at intersections has little correlation with the total approach length and average maximum queue lengths show some positive trends with an increasing variance with increasing length. However, given that longer queues can be observed only where there is enough approach length to accommodate them, this small correlation is not deemed strong.

Further, Figure 27(a) shows that shorter approaches tend to have far more spillbacks than longer approaches. Spillbacks occurred regularly on short approaches. All these spillbacks correspond to the slanted boundary line in Figure 27(b) where the queue length is equal to the approach length. All the other points in Figure 27(b) present situations where some queues were observed but were shorter than the entire approach length.



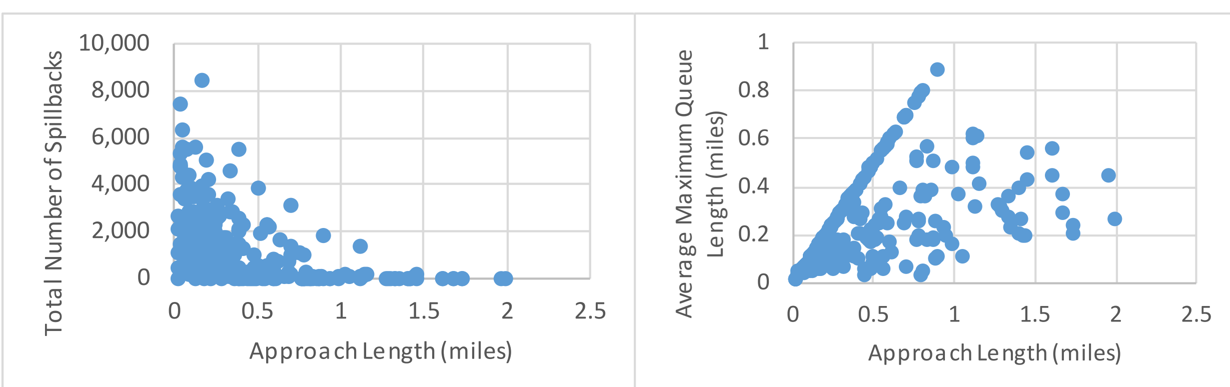
(a) (b)

Figure 25. Intersection Bottleneck Delay Comparison to (a) Intersection Length-Weighted AADT, and (b) Intersection Total Approach Length. AADT = annual average daily traffic.



(a) (b)

Figure 26. Comparison of Intersection Total Length to (a) Total Number of Spillbacks, and (b) Average Maximum Queue Length



(a) (b)

Figure 27. Comparison of Approach Length to (a) Total Number of Spillbacks, and (b) Average Maximum Queue Length

Cross-Comparison of Measures

A matrix of scatter plots among the different performance measures was also briefly studied to explore any indications of strong correlations among those measures. An example of such a matrix plot is provided in Figure 28. Some measure pairs, such as average VMT per bottleneck and average delay per day, have a slight correlation. No unexpected patterns or anomalies were observed in these plots.

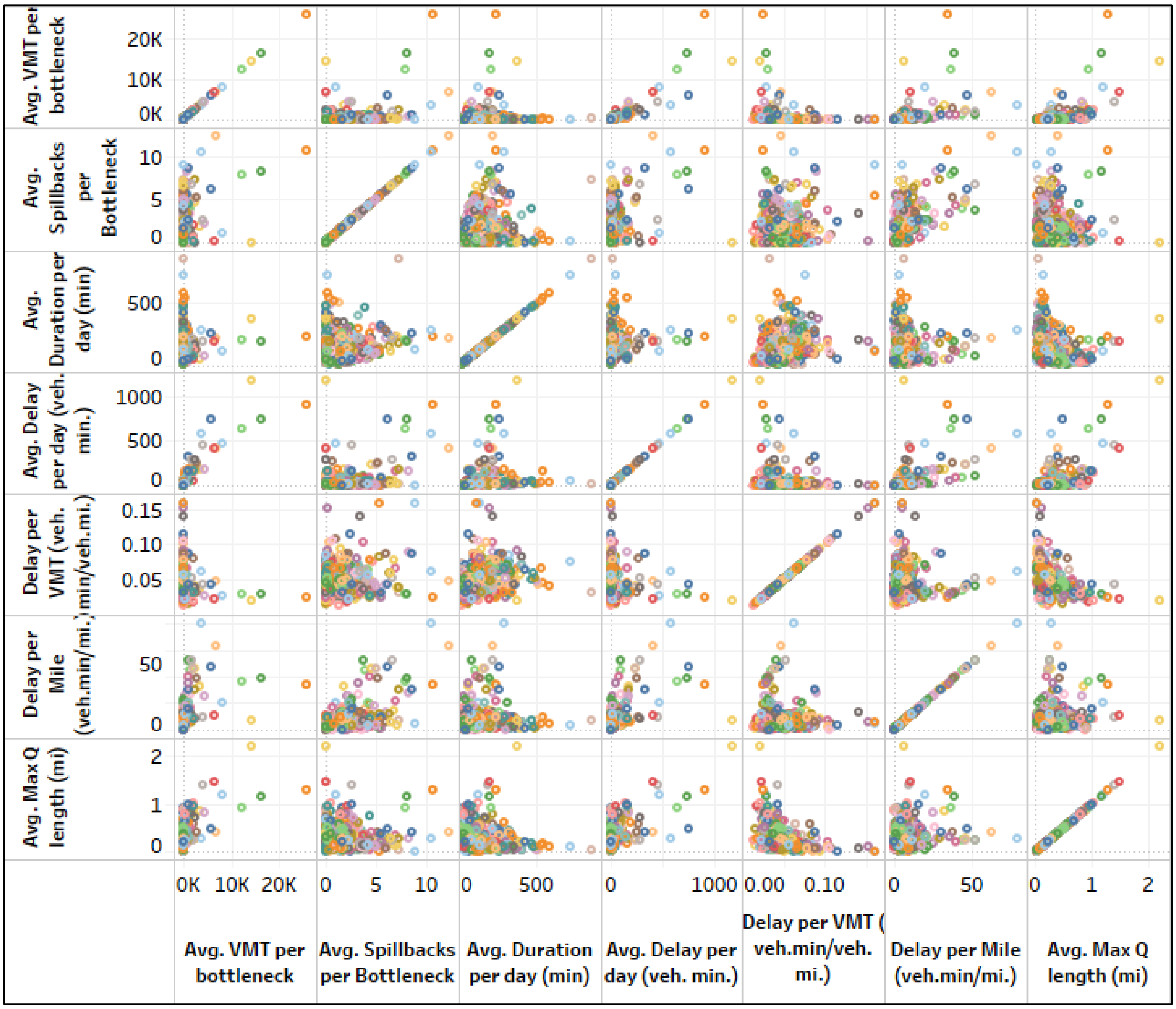


Figure 28. Matrix of Scatter Plots Across Select Performance Measures. Each color represents a different intersection. VMT = vehicle miles traveled; min = minutes, mi = miles; veh.min = vehicle-minutes; veh.mi = vehicle-miles; Max Q = average maximum queue length.

Task 5: Validation of Results and Identification of Potential Use Cases

Several field experts were engaged in this study both to validate the case study results and to identify use cases for this methodology.

Validation of Results Through Expert Review

As mentioned earlier, the node-link concept used in this study is fundamentally different from the link-based analyses in the other bottleneck identification tools available to VDOT. Therefore, results from this study could not be directly compared to those of other studies for a quantitative, statistical analysis to examine the relative performance of this method. Therefore, field experts were engaged to review and validate the results using their knowledge of the local area traffic and conceptual expectations. Experts provided a wide range of feedback including on the results, performance measures, visualizations, and implementation concerns and opportunities.

The first expert panel consisted of VDOT Northern Region traffic engineering staff with extensive experience and knowledge of traffic operations in the study area. Two sets of results using LTS and Method I were presented to the panel, one each for the A.M. and P.M. peak periods. The panel examined the top 15 bottlenecks in both sets of results and concluded that the results were quite consistent with field observations. Two specific case examples show the benefits of quantifying the delays and other performance measures to identify bottleneck intersections consistently and accurately and to support the field staff with data-driven decisions. In the first case, some panel members thought the rank of intersection VA-684 and VA-694/Great Falls St was not appropriate because they expected this intersection to rank lower than some of the other major intersections. However, further internal discussion among the panel revealed that it was indeed possible that this intersection was carrying high volumes and having more delays, especially as drivers heading to the Tysons Corner area in the A.M. peak period try to avoid other major congested roads and given that it is a skewed intersection.

The second case example concerns the intersection that was ranked 15 by Method I and 22 by Method II in Table 4. Field experts shared their observation of similar trends on Google Traffic elsewhere in the study area where an approach section closest to the intersection was often green (not congested) whereas its immediate upstream section was often red (congested); that is, Method I would produce much higher delays than Method II for those intersections. Such field situations can result from turning movements obstructing the main movement or from access points or bus stops close to the intersection.

A second panel consisted of experts in traffic engineering, planning, operations, and research, mainly from VDOT's Central Office. Given this panel's knowledge of other corridors and networks in the state and related statewide programs underway, their validation focused on performance measures, visualizations, data concerns, research recommendations, and implementation details rather than on the specific bottlenecks in the study network. Both panels expressed some concerns about the quality of probe data and the availability and completeness of the various datasets. In response to these expert panel concerns, a number of new output fields were added to the results including the average confidence score as a measure of XD speed data credibility, completeness from an XD segment definition and AADT availability perspective, average approach AADT, and length-weighted total AADT at an intersection. However, as discussed earlier, speed data quality has not proved to be a major concern in this study. Further probe data vendors are increasingly providing traffic volume estimates that may supplement VDOT traffic volume data in the future. Per panel request, a filter was added to enable users to focus on their agency jurisdiction.

Potential Use Cases

With the background of the research methodology, visualization tool, case study results, and known data concerns, field experts and the research team identified the following potential use cases for implementation of this research:

- Localities can use such a screening tool to identify top bottlenecks and their details for project prioritization and planning, specifically for SMART SCALE applications (VDOT, 2018a). Several localities lack the staff resources in terms of time and skillset to analyze disparate data sources and need easy-to-use, data-driven tools.

- OIPI staff can potentially improve the congestion analysis methodology used by the SMART SCALE team for evaluating applications from localities and for prioritizing projects. However, this methodology can be used only where roads and data are already in existence. New facilities and facilities without data are beyond the scope of such application.

- Localities and OIPI can also potentially use this methodology and tool to perform before-after evaluations, specifically where projects have been implemented through SMART SCALE. A small-scale pilot implementation is needed to identify the scope of application of this tool for this use case. For example, if an intersection was not severely congested in the before period or if transit solutions were implemented, the current study methodology might be unable to detect the project benefits.

- VDOT staff can identify congestion problem areas, sources of congestion (such as recurring or incident related), and solutions. One DTE is interested in combining the bottlenecks with known safety hot spot locations to identify top needs in his district.

- Regular and consistent assessments can help VDOT identify locations and time periods where additional data (in quantity, quality, or type) are needed to identify and characterize congestion bottlenecks better.

- One DTE saw the bottleneck rankings as a communication tool to work with his local jurisdictional staff on the topic of congestion mitigation.

- Extending this study by including details such as freight tonnage will help identify arterial bottlenecks specific to freight; this is needed for long-range planning.

In general, the data-driven process in this study was preferred to anecdotal references for all of these purposes.

CONCLUSIONS

- *The case study application, expert validation, and feedback served as a successful proof of concept for the proposed link-node–based traffic bottleneck identification methodology and helped identify specific methodological details of high interest for future implementation. According to expert feedback, this methodology complements the prevailing link-based approaches, which are more appropriate for corridors.* This study proposed and tested a new methodology based on a link-node concept that used high spatial resolution probe data (e.g., INRIX XD data) and considered the performance of all intersection approaches toward identifying and ranking intersection bottlenecks. The methodology was applied to a network in Northern Virginia consisting of 245 nodes and 1,096 XD segments.

- *Of the three reference speeds examined in this study, the LTS from overnight hours emerged as the most reasonable choice for future application.* The average observed speeds were consistently lower than the PSL on some segments, creating cases where segments were marked as congested for very long periods, such as several months. Observed speeds were consistently higher than the vendor-reference speed on other segments, creating situations where such segments were never marked as congested over the entire study period. LTS provided a reasonable balance between these two extremes.

- *The top ranked bottleneck intersections from the two queue length calculation methods (i.e., any approach segment congested [Method I] versus a strict order of segments from the node being congested [Method II]) were usually similar. Method I was computationally faster than Method II.* The correlation coefficient between the rankings from the two methods was high, at around 0.96. The Wilcoxon rank test showed that the ranks from the two methods were different at a 95% confidence level, but this statistical test neither proved that the methods were similar nor proved that they were very dissimilar. The two methods may simply serve different applications, such as node-level congestion analysis and access-related congestion analysis.

- *Conflation and missing data are two main concerns identified during this study that could considerably affect scaling up this methodology to a larger geographical area.*

  — *Conflation of the various sources of data and their underlying reference systems was a labor-intensive effort.* Segment definitions usually change over time when vendors update their maps, which demands ongoing maintenance of the conflation results. However, as more agencies are interested in such analysis tools, the data providers and consultants are expected to fill this gap.

  — *Unavailability of traffic volumes (AADT) and/or probe speed segments on minor roads and private approaches is a concern for some signalized intersections.* This challenge will likely continue into the future, even with increasingly denser XD segmentation and higher coverage of probe data. However, probe speed data vendors and other researchers are working on methodologies to estimate and provide traffic volumes as part of their data offering. StreetLight Data already provides such ubiquitous AADT data for 2017 (Schewel, 2018).

- *Traffic engineers, planners, metropolitan planning organizations (MPOs), and OIPI are interested in applying the results of such a screening tool to several use cases.* Expert validation and feedback revealed a high interest to expand the study network and use the results. The study identified several practical use cases for this methodology and its results. The developed data-driven, sketch planning/screening tool can help to prioritize high value capacity and operational improvement projects and to evaluate the benefits of those projects. The case study and the expert panel validation show that the proposed methodology has great potential to be implemented in an agency's operation and planning programs.

- *There were no obvious data quality concerns regarding the probe speed data for ramps and arterials.* The quality of the ramp travel time data was relatively less understood at the start of this study, with few known studies using that dataset. However, this study focused only on the relative rank of delays on the various approaches, including ramps.

- *Transferring the results from this study to other locations and time periods needs to be tempered appropriately.* This study examined one urban network with around 250 intersections, using 9 months of data.

RECOMMENDATIONS

1. *VTRC should continue to stay abreast of progress made by VDOT vendors and consultants working on travel time data conflation (INRIX and iPeMS) and regularly update VDOT's TED, OD, and TMPD. Once commercial conflation solutions are available or when VDOT decides to proceed ahead independently, the TED, OD, and TMPD should pursue development of an arterial bottleneck identification and characterization tool using vehicle probe data and scope the tool using the lessons learned from this study.* Third parties, including INRIX and Iteris, are interested in and working on related conflation topics and will likely have usable products in the next 12 to 18 months. DTEs and MPOs are interested in using the results of such a tool for decision making, project prioritization, and communication. The timing of such a development should also consider the status of these four closely related topics: automated traffic signal performance measures (ATSPM), centralized signal system (CSS), vehicle probe trajectory data uses, and connected automated vehicle research and deployment. Although ATSPM and CSS are limited to signalized intersections, the methodology developed in this study is also applicable to non-signalized intersections.

2. *VTRC should conduct a pilot study of this methodology with more stakeholders and document the findings.* VTRC has been in discussions with OIPI and VDOT's STARS Program regarding before-after evaluations of select SMART SCALE and STARS intersection projects, respectively. VTRC has also been in discussions with the VDOT Culpeper District Traffic Engineering Division, the VDOT Staunton District Planning Division, and the Albemarle County Planning Division to analyze select intersections in their areas. VTRC will partner with one or more of these and other potential stakeholders and specifically study rural intersections. VTRC should apply this study methodology, analyze

the results, and provide the visualization tool to the stakeholder(s). VTRC should also submit a technical memorandum to the stakeholder(s) and the TRP documenting the strengths and limitations of such an application of this methodology for various project types, road classes, and other site characteristics. OIPI has also expressed interest in using contract services to scale up the conflation efforts to a large network such as the Corridors of Statewide Significance (CoSS) first and then to the entire state. However, the timeline for such action is currently under discussion between VTRC and OIPI.

3. *Whenever VDOT's TED, OD, and TMPD determine to be appropriate, VTRC should initiate a future phase(s) of research on the sub-topics identified in the study.* These topics include accommodations for missing approaches or data, accommodations for small approach lengths, super nodes, alternate intersections, and number of bottlenecks (their durations and gaps).

IMPLEMENTATION AND BENEFITS

Implementation

Implementation of the recommendations of this study depends on a number of external factors such as the use of trajectory data by the transportation industry, further development and use of ATSPM by VDOT, and availability of ongoing node-link conflation services by third party vendors. Given this context:

Regarding Recommendation 1, VTRC should keep abreast of the progress of conflation for 1 year, from November 2018 through October 2019. VDOT's TED, TMPD, and OD should develop the bottleneck tool in FY20-FY21.

Regarding Recommendation 2, VTRC should implement the pilot study between March and August 2019.

Regarding Recommendation 3, the TED, TMPD, and OD should implement the recommendation in the next 2 years, with the exact start date depending on a number of external factors documented in Recommendation 1.

Benefits

VDOT field staff currently do not have access to a tool based on the methodology developed in this study. OIPI, DTEs, and MPOs are all interested in the methodology and tools developed in this study to improve their decision making for project prioritization and to improve communications among various stakeholders. All of these applications will result in the following benefits: better investment of limited funds, more effective project selection, and timely and accurate evaluation of implemented projects.

Implementing Recommendation 1 will cater to this main unmet need, and implementing Recommendations 2 and 3 will support the fulfillment of Recommendation 1. Together, implementation of these recommendations will also improve the state of the art and practice throughout the transportation industry in arterial bottleneck identification, understanding, and ranking.

SUGGESTIONS FOR FURTHER RESEARCH

Further research and analysis are needed to overcome some data and methodology limitations and to enable large scale implementation. Specific research topics identified during the course of this study include the following:

- *Estimate total intersection performance measures including approaches with missing data and short approach lengths.* Until such research is completed, the TRP wanted to include intersections with partial data availability in the analysis along with data completeness indicators so as to enable the highest use of the data and proper interpretation of the results.

- *Investigate the parameters of super nodes and their impacts on total bottleneck rankings.* Given the short lengths of ramps and some approaches and that closely spaced signals such as at an interchange are often operated together, all these nodes may be better served by studying them together as a "super node."

- *Investigate the relationship between access density and differences in delays from Methods I and II.* Access density details need to be collected.

- *Examine different threshold speeds such as 40% to 50% of PSLs or 70% to 80% of INRIX reference speed.* For some use cases such as SMART SCALE, the use of PSLs is preferred. Based on the results from this study, a different threshold of other reference speeds may yield more reasonable results.

- *Identify the causes of the bottlenecks in order to determine appropriate infrastructure and operational solutions and recommendations for bottleneck solutions.* In summary, the TRP wanted "to convert bottlenecks into projects, and apply for appropriate grants." Given the solution selection usually involves engineering judgment, site-specific characteristics of interest to be presented with the final bottleneck results (with filtering ability) include geometric factors such as grade, curvature, number of lanes, lane width, median type and width, and accesses; numbers and patterns of incidents/crashes; traffic volume in peak hours by season (summer travel, school zones); and school speed zones. MPOs might have geometric data available for non-VDOT roads, especially at or above the collector road classification. As a further extension, a detailed, internal dashboard with drill down and automation capabilities is desired. Further, turning movement counts and speeds are currently not available widely. Future availability of this dataset would support the identification of bottlenecks as well as some of their major causes, such as turn bay queue spillbacks.

- *Analyze the patterns in bottleneck durations and counts to distinguish actual congestion in the field from concerns with the data or concerns with the algorithm.* Recurring bottlenecks are conceptually expected to start and end at timestamps that allow easy comparison of the number of bottlenecks across locations and time periods, as well as normalization of performance measures with such bottleneck counts. However, starts and ends of bottlenecks may display large variances in durations and gaps and large variations across days. In this study, using 15-minute aggregated speed and volume data, several bottlenecks resulted with 15-minute durations and/or 15-minute gaps. Further study is necessary to isolate these concerns.

- *Investigate non-recurring bottlenecks and their impacts on networks.* Understanding these impacts for past traffic incidents, special events, weather events, and work zones will be useful to identify traffic operations plans for such events in the future and to improve communication with the public. Some non-recurring bottlenecks could also be potentially mitigated with low-cost geometric and operational solutions. VaTraffic currently captures lane closure data but not intersection level data. Some special events (e.g., the 9/11 Memorial Day) are archived in VaTraffic. VDOT currently has no record of non-recurring events in independent cities even though they affect traffic on VDOT roads (e.g., University of Virginia sports events in Charlottesville).

- *Investigate the advantages and disadvantages of applying the methodology developed in this study for freeways and interchanges.* This study focused extensively on arterial intersections. Based on the literature reviewed, vehicle delay is widely used for bottleneck identification. However, bottlenecks at the interface of freeways and arterials and their impacts on multiple roadways have not been studied in detail.

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