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# Identification of Locations and Causes of Unreliable Travel Times on Virginia Freeways

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**Final Report VTRC 22-R17**

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

**Standard Title Page - Report on Federally Funded Project**

| 1. Report No.:<br>FHWA/VTRC 22-R17 | 2. Government Accession No.: | 3. Recipient's Catalog No.: |
|---|---|---|
| 4. Title and Subtitle:<br>Identification of Locations and Causes of Unreliable Travel Times on Virginia Freeways | | 5. Report Date:<br>March 2022<br>6. Performing Organization Code: |
| 7. Author(s):<br>Chien-Lun Lan, Ph.D., and Ramkumar Venkatanarayana, Ph.D., P.E. | | 8. Performing Organization Report No.:<br>VTRC 22-R17 |
| 9. Performing Organization and Address:<br>Virginia Transportation Research Council<br>530 Edgemont Road<br>Charlottesville, VA 22903 | | 10. Work Unit No. (TRAIS):<br>11. Contract or Grant No.:<br>117143 |
| 12. Sponsoring Agencies' Name and Address:<br>Virginia Department of Transportation<br>1401 E. Broad Street<br>Richmond, VA 23219 | Federal Highway Administration<br>400 North 8th Street, Room 750<br>Richmond, VA 23219-4825 | 13. Type of Report and Period Covered:<br>Final<br>14. Sponsoring Agency Code: |
| 15. Supplementary Notes:<br>This is an SPR-B report. | | |


16. Abstract:

Travel time unreliability on roadway networks and its mitigation continue to be increasingly strong focus areas for many transportation agencies. Although the transportation agencies and motorists are often interested in improving corridor and network travel time reliability, the predominant state-of-the-art methods available to practitioners focus on individual "hotspots."

This study first developed a systemic approach to calculate travel time reliability measures to analyze limited access facility links along with their detour routes or in conjunction with their upstream/downstream links. A novel network screening methodology for travel time reliability called the "Top 20-20" method was then developed that considered the hotspots (relatively smaller links) in conjunction with their spatiotemporal contexts. Methods for performing corridor causal event analyses in conjunction with the causal events at the link hotspots were also developed. These methods were applied to a large 2,800-mile limited access facility network in Virginia. A qualitative validation of these methods and their results was conducted using an expert panel, and the concepts were found to be sound. The validation expert panel identified several use cases for these planning-level methods and results, including travel time reliability needs identification for long-range planning and development and implementation of operational strategies for improving travel time reliability on corridors and in networks.

The study recommends that the Virginia Department of Transportation (1) consider applying systemic analyses wherever corridor travel time reliability is the main focus; (2) conduct additional research to further the developed methods; and (3) pursue computational resources needed to carry out the systemic analyses.


| 17 Key Words:<br>Travel time, reliability, network, screening, corridor, causal analysis | | 18. Distribution Statement:<br>No restrictions. This document is available to the public through NTIS, Springfield, VA 22161. | |
|---|---|---|---|
| 19. Security Classif. (of this report):<br>Unclassified | 20. Security Classif. (of this page):<br>Unclassified | 21. No. of Pages:<br>63 | 22. Price: |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

**FINAL REPORT**

# IDENTIFICATION OF LOCATIONS AND CAUSES OF UNRELIABLE TRAVEL TIMES ON VIRGINIA FREEWAYS


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

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

Charlottesville, Virginia

March 2022
VTRC 22-R17

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# ABSTRACT

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This study first developed a systemic approach to calculate travel time reliability measures to analyze limited access facility links along with their detour routes or in conjunction with their upstream/downstream links. A novel network screening methodology for travel time reliability called the "Top 20-20" method was then developed that considered the hotspots (relatively smaller links) in conjunction with their spatiotemporal contexts. Methods for performing corridor causal event analyses in conjunction with the causal events at the link hotspots were also developed. These methods were applied to a large 2,800-mile limited access facility network in Virginia. A qualitative validation of these methods and their results was conducted using an expert panel, and the concepts were found to be sound. The validation expert panel identified several use cases for these planning-level methods and results, including travel time reliability needs identification for long-range planning and development and implementation of operational strategies for improving travel time reliability on corridors and in networks.

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## INTRODUCTION AND BACKGROUND

Identifying and mitigating travel time reliability "hotspots" on roadway networks continue to be increasingly strong focus areas for many transportation agencies across the nation (Schrank et al., 2019; Taylor and Chang, 2017; Virginia Department of Transportation [VDOT], 2021). In addition to its focus on hotspots, VDOT has explicitly included travel reliability as an important goal in recent corridor studies (VDOT, n.d.; VDOT et al., 2020). Indiana mobility reports also show the desire and intent to analyze travel times of corridors implicitly (Joint Transportation Research Program, Purdue University [JTRP], 2021). From the motorist perspective as well, the interest in improving travel reliability is often focused in terms of trips that span several miles along corridors and across roadway networks (Carrion and Levinson, 2012). However, the predominant state-of-the-art method for screening unreliable travel time locations (such as traffic message channels [TMCs] or other small spatial segmentation) is by analyzing unreliability at each location individually, independent of other nearby locations (Cambridge Systematics et al., 2013; JTRP, 2021; Taylor and Chang, 2017; VDOT, 2021). The performance measures used in traditional reliability screening include planning time index (PTI) and level of travel time reliability (LOTTR) (JTRP, 2021; Taylor and Chang, 2017).

Although this traditional method has inherent advantages of being simple to compute and communicate, it also largely ignores (1) the spatial context of nearby links on the same or other nearby roads whose reliability is intertwined with the link under study, and (2) the temporal context of unreliability on neighboring links. Thus, the traditional approach may or may not identify links of interest for supporting vital agency goals targeted at improving travel time reliability along corridors or across networks. The literature is limited on the topic of analyzing link travel time unreliability considering spatiotemporal contexts. However, interest in analyzing larger corridors and networks for travel time reliability has been slowly growing over the last 10 to 15 years, emphasizing the need for newer methodologies and tools to better understand, identify, communicate, and solve roadway travel time unreliability problems in these contexts. The reviewed literature is presented here as a background for this study.

Dowling (2007) defined a travel time index for a network in terms of vehicle-hours traveled. Tu et al. (2013) studied macroscopic travel time reliability diagrams for freeway networks using traditional traffic volume and density measures. Lasley et al. (2014) developed a “total peak period travel time” performance measure as the sum of the travel times of all the vehicle travel times in a network for the entire peak period to bridge mobility and accessibility measurements better. List et al. (2014) compared the actual vehicle travel times on relatively longer corridors to the sum of the percentile travel times (at 5% intervals) at the constituent links and found them to be similar. Brennan et al. (2018) developed a “travel time inflation” concept for a network as the sum of the extra time taken by a motorist on all the links in a network beyond the free-flow travel time (FFTT). However, this summation of the average delay on all links without a volume weight would treat major freeways and minor arterials equally. Saedi et al. (2020) used the mean and standard deviation of travel rates as measures of reliability for analyzing networks using Network Fundamental Diagram. The 2020 Maryland mobility report (Beckett et al., 2020) analyzed relatively longer corridor sections as a whole, but it is not clear if the temporal or causal-event correlations between the link unreliability and the corridor unreliability were tracked.

Lan et al. (2020) expanded upon these prior efforts to analyze regional travel time reliability of an entire network, adapting the total system travel time (calculated as the sum of the travel times by all the vehicles on all the network links) concept used in the traffic simulation-modeling field (Mannering et al., 2009). In their method, one first calculates the regional total travel time for each date-hour timestamp, then the regional FFTT as the weighted sum of the FFTTs of individual TMCs, and finally the regional PTI as the ratio of these two quantities. The current study builds on these regional travel time reliability concepts and measures for corridors and uses the more generic “systemic” designation. In essence, systemic travel time, systemic FFTT, and systemic PTI are the terms used in the current study. This systemic approach also enabled the combined causal analyses of links and their corridors when both of them experienced unreliable travel times. The causes of travel time unreliability have traditionally been considered the same as the causes of congestion, such as incidents, work zones, and weather events (List et al., 2014; Transportation Research Board, 2019).

In contrast to the systemic approach, wherever PTI for a higher spatial aggregation (such as a corridor or a network) was needed, it was traditionally calculated as a weighted sum of the PTIs of the constituent lower spatial aggregation of links, such as TMCs (Venkatanarayana, 2017). Although these weights could be volumes, lengths, vehicle miles traveled (VMT), etc., differences among reliability measure values using different weights seem to be insignificant (Venkatanarayana, 2017). These traditional corridor PTI values can also be used to perform a simpler and limited network screening for link reliability using its corridor context, which was also explored and discussed in this study.

Since the newly developed methodology has no parallels in the state-of-the-art methods, both its concepts and the case study results were validated through qualitative feedback from the technical review panel (TRP) and a broader advisory panel (AP) of VDOT staff. Direct feedback from and further use cases identified by these experts indicate promising new benefits for transportation agencies from this new screening methodology.

## PURPOSE AND SCOPE

The purpose of this study was to develop systemic travel time reliability measures for limited access facility (LAF) links, both independently and with detour routes, to analyze the systemic travel time reliability measures relative to traditional measures and for factors affecting the measures and to explore the use of systemic travel time reliability measures for causal analyses and network screening.

LAFs in Virginia were the main focus of this study. Some interstate links were also studied in conjunction with select detour routes. Causes studied in this project were incidents, work zones, road conditions, precipitation events, and holidays. The exploratory and proof-of-concept nature of this study constrained the validation to a qualitative approach.

## METHODS

The study was carried out in five main tasks:

1. data collection and preprocessing
2. calculation and analysis of travel time reliability performance measures
3. design and application of systemic screening methodology
4. combined causal analyses of links and corridors
5. validation of results.

Some of these tasks were carried out in an exploratory and iterative manner, with the results from each task feeding the development of other tasks. Given this iterative nature of the work, the newness of a number of details of the methodology, and the results in this study, in the interest of clear communication, details of methods and results for some tasks are presented together with clear examples and the researchers' discussion in the next section. For those tasks, this section presents a simple overview.

### Task 1. Data Collection and Preprocessing

#### Description of Study Area and Time Periods

The study network for this project, determined in conjunction with the TRP and the AP, consisted of nearly 2,803 directional miles of roads, including all interstates and all LAFs longer than 10 directional miles in Virginia (see Figure 1). This network is diverse in many ways, including traffic volumes, truck percentage, vertical grade, weather pattern, number of lanes, ramp density, available detour facilities, and urban-suburban-rural traffic patterns. This large study area results in large input, intermediate, and final results datasets, which required different computational approaches than used normally.

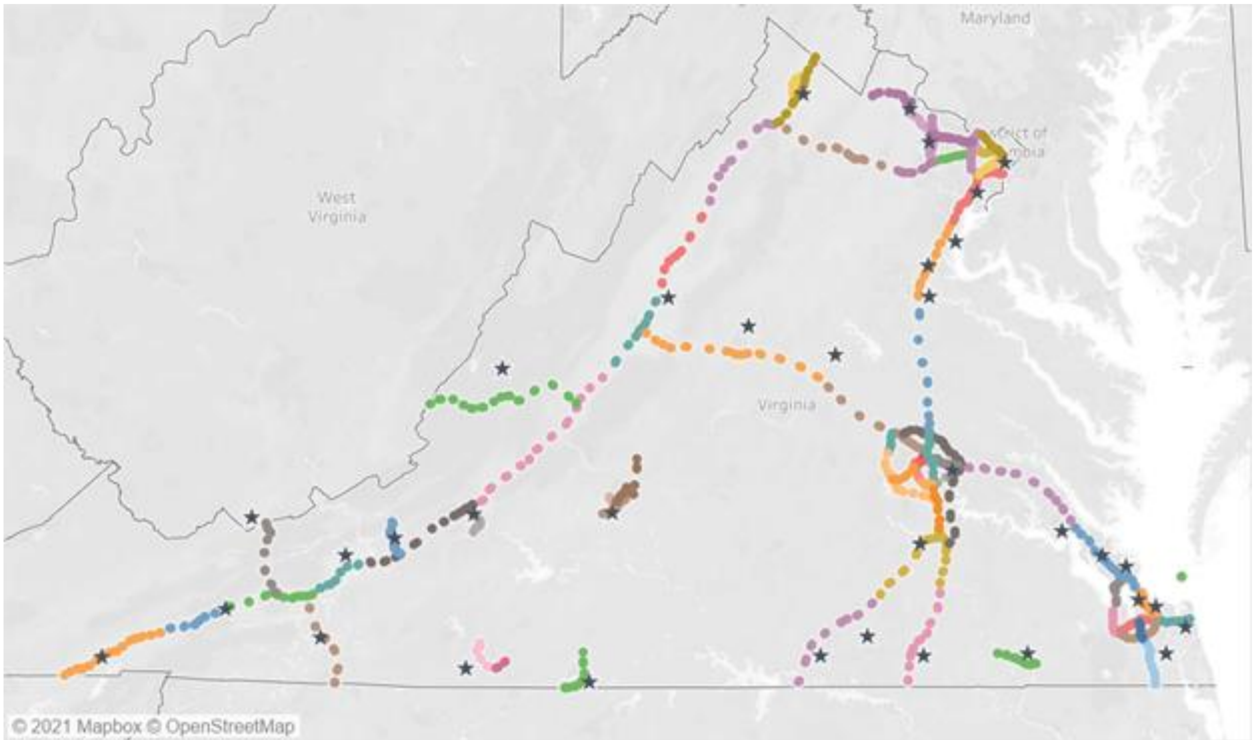



**Figure 1. Study Network With Link Midpoints Shown as Dots. Corridors are represented by dot color, and weather stations by black stars.**

All datasets were obtained for the 4-year period 2016-2019 and were aggregated to 1-hour intervals. The standard MAP-21 reliability time periods, i.e., from 6 AM to 8 PM on each day of the year, divided into four groups—AM peak, midday, PM peak, and weekend—were used in this study. The 2019 AM peak period was used to illustrate all the numerical examples in this report.

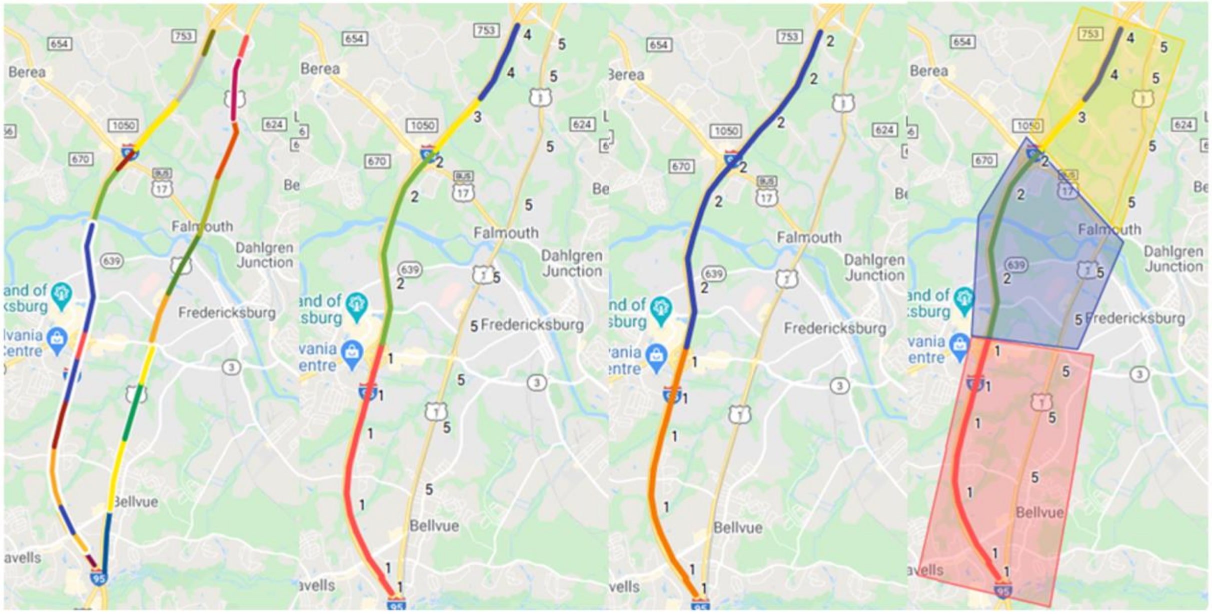
## Travel Time Dataset and Segmentation

The primary input dataset for this study was the vehicle probe travel times procured by VDOT from a third party vendor, INRIX. The spatial units for these data are defined by directional stretches of roadways with lengths under 1 mile, called "XD segments" (see Figure 2[a] for an example). The most recent INRIX XD segment map available at the start of the study (Version 20.1) was used as the base network. The entire list of XD segments of interest for this study was identified after the links (explained next) were identified. Python codes were developed to download the data using the INRIX data download Application Program Interface (API). This was the only known way to obtain all 4 years of data using a specified map version. Table 1 shows the details of these different spatial segmentations.

The primary spatial unit of analysis in this study was a "travel time link," or simply "link," used by VDOT's Operations Division (OD) for many agency operational analyses. An LAF link is defined as a directional stretch of roadway between two adjacent interchanges (see Figures 1 and 2[b] for examples). The link definition files were obtained from the OD, verified using ESRI ArcGIS and Tableau, and manually updated as needed. Links on arterials are not predefined within VDOT and were, therefore, custom developed in this study. The extents of the arterial routes of interest that formed reasonable detours to some interstates were first identified in conjunction with the TRP. Locations where the crossroads from the interstate ramps connected with the detour routes were used as the termini for the detour links. By the use of a conflation tool developed previously for VDOT (Zhao and Venkatanarayana, 2019), all XD segments belonging to each link were first identified. The results were verified by visual inspection in ESRI ArcGIS, and any missing XD segments in comparison to the INRIX XD map files were added manually.

A "corridor" was defined as a directional stretch of a LAF containing several contiguous links with some significance to the jurisdictional or motorist travel perspectives (see Figures 1 and 2[c] for examples). First, the city and county jurisdictional boundaries were obtained from VDOT's GIS (geographic information system) group and spatially joined with the link shapefile using ArcGIS. Wherever a jurisdiction-level aggregation yielded fewer than three links per direction for a route, such a road stretch was combined with its neighboring jurisdiction to form a more reasonable stretch of interest to this study, wherever reasonable. In addition, if other major LAFs crossed a route or at tunnels, with known, significant changes in traffic patterns, such boundaries were also manually selected as termini for corridors. This approach is inherently subjective and requires manual, expert inputs. The researchers used their personal knowledge of the traffic patterns in the study area to define the corridors as an example application of the concept in this study; the termini for corridors can easily be changed for other applications.

A "section" was defined as a directional stretch of a LAF containing one or more continuous links as well as their parallel arterial/detour link(s) in the same direction. All the XD segments within one detour route were grouped together as one detour link. If a second detour route was identified, the XD segments on this route were grouped together as a second detour link. In essence, all links on the LAF were joined end to end, and all detour links were side-by-side to each other and to the LAF. In response, a number of arterial links were included in this study in addition to the LAFs. A total of 70 sections were selected for this study, including I-95 and US-1 near Fredericksburg; I-95, US-1, and US-301 North of Richmond; I-64 and US-60 East of Richmond; I-64 and US-250 near Afton Mountain; and I-81 and US-11 (see Figure 3). Three of these sections contained two detour links each, and six other sections contained two links each. These link combinations were purposely selected to develop the calculation methodologies that apply to all possible situations.




(a) (b) (c) (d)

**Figure 2. Example Illustrations of Spatial Segmentations Used in This Study: (a) INRIX XD segments; (b) links (constrained by adjacent interchanges); (c) corridors (unconstrained by adjacent interchanges); (d) sections (that include one or more interstate links and parallel arterial link[s]).**

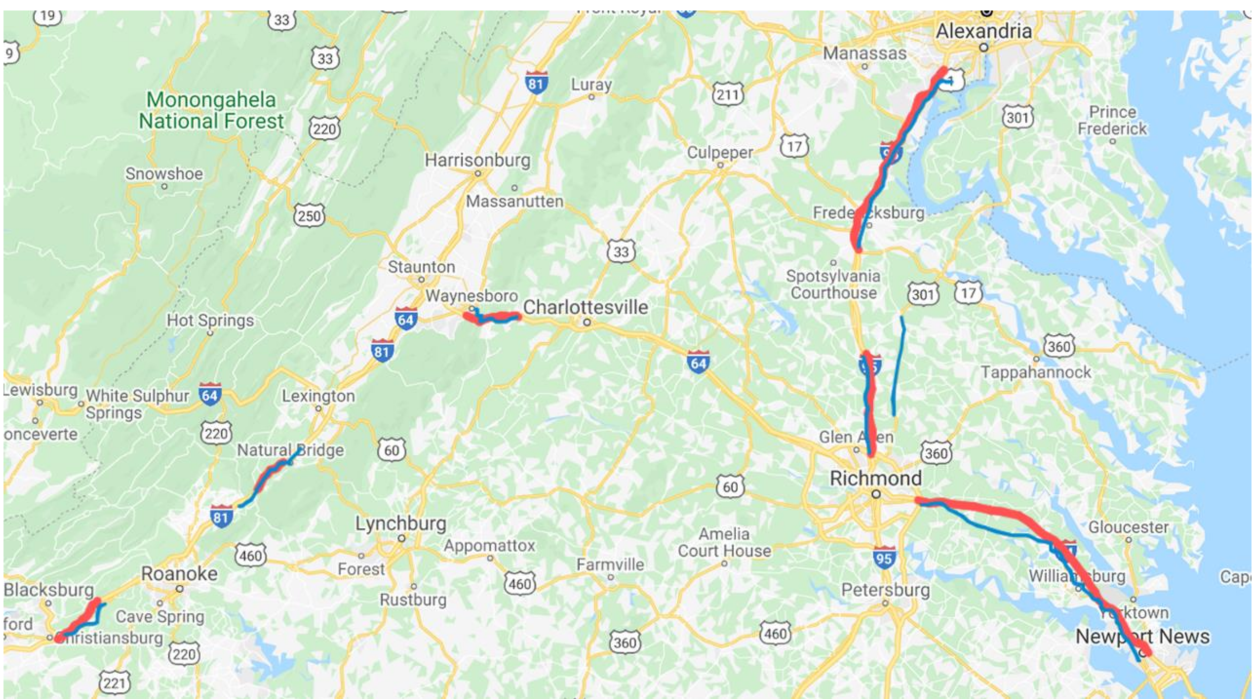



**Figure 3. Sections Studied in This Study. Red lines are interstates; blue lines are detour routes.**

**Table 1. Features of Spatial Segmentations Used in This Study**

| Segmentation Type | No. of Element | Average Length (mi) | Length Range (mi) |
|---|---|---|---|
| XD segment | 5,518 | 0.51 | 0.08-0.992 |
| Link: LAF | 1,125 | 2.49 | 0.14-19.69 |
| Link: Detour | 73 | 4.48 | 1.12-14.62 |
| Corridor | 162 | 19.3 | 0.73-61.83 |
| Section | 70 | LAF: 4.2<br>Detour: 4.5 | LAF: 0.8-12.5<br>Detour: 1.1-14.6 |

LAF = limited access facility.

## Other Datasets and Conflation

Several event datasets were used to analyze the causes of travel time unreliability. Incidents, work zones, and roadway conditions (e.g., icy road) were obtained from VDOT's VATraffic database. These events contain start and end date times, start and end latitudes and longitudes, roadway, and direction; events on the interstates contained the mile markers as well. Interstate events were conflated to the links using the start/end mile markers. Although this was not perfect, it was deemed to be of sufficient accuracy for this study. Since LAFs and detour route links did not always have start/end mile markers, events on those links were conflated using ArcGIS spatial join with the latitude and longitude attributes and with a buffer of 50 ft, and the roadway-direction fields in the events dataset and the link definition file were compared in Excel to verify accurate matches.

Only incidents with both lane closures and durations longer than 30 minutes were considered for this study. Only significant lane-impacting work zones and road conditions were considered. Lan et al. (2019) provided more details on event filtering. Precipitation data from the National Weather Service were downloaded from the National Climatic Data Center for all weather stations in Virginia (see Figure 1) and were aggregated to hourly intervals. These weather stations were mapped to the links by their geographical proximity. Lan et al. (2019) provided more details. Only hourly records with precipitation more than 0.25 in/hr were considered for this study. If a link-hour was affected by roadway condition or precipitation, it was marked to be affected by "weather." Holidays and dates associated with holiday travel observed in Virginia were obtained from the VDOT Traffic Engineering Division (TED) database and attached to the travel time data by date for all XD segments.

Since incidents and work zones on a link often have queue impacts on other links farther upstream, and for a time period beyond the end of the events themselves, for each link on the Virginia interstate network, VDOT's OD has identified all the upstream links of interest (including those on other interstates connected via interchanges). The number of upstream links for a given link depends on the network topology and known traffic congestion impacts in the area and may extend up to 5 to 10 miles (see Figure 4 for an example). For example, although links at the start of interstates often have no upstream links, a link on I-264 Eastbound with close interchange connections to different directions of I-64 and I-464 has as many as 28 upstream links. The definitions files for the upstream links were also obtained from VDOT's OD, verified using ESRI ArcGIS and Tableau, and manually updated as needed. If a link-hour was affected by an incident, then all its upstream links for that hour and the next hour were marked as affected by incident impact.

**Figure 4. Illustration of Upstream Links (on I-66 Eastbound, I-495 Northbound, and I-495 Southbound in Blue) for a Given Link (on I-66 Eastbound in Red)**

Traffic volumes were used to weight traditional travel times and travel time reliability measures. Annual average daily traffic (AADT) and average volume profile factors for each day-of-week and hour were obtained for each TMC from VDOT's OD and TED. These data were conflated to the XD segments in Excel using XD-primary-TMC crosswalk tables from INRIX. XD AADT was multiplied by the XD volume profile factors to obtain hourly XD traffic volumes. For any timestamp, link volumes were calculated as the length-weighted sum of the volumes of the constituent XD segments.

The average truck percentage by TMC for 2019 was obtained from the National Performance Management Research Dataset (NPMRDS). Since the study network in this project included only National Highway System roads, all of which are covered by the NPMRDS, this dataset and level of aggregation were sufficient for this study. Using the XD-TMC crosswalk table, the XD truck percentages were determined using Excel. The number of lanes at each link was obtained from the Open Street Maps (OSM) web repository (Open Street Maps, n.d.) using Python codes and lat-longs of the first two XD segments in the link. Wherever the numbers from the two XD segments did not match, Google Street View was used in conjunction with the XD lat-long values to verify the field conditions and to determine manually the number of lanes and code it into an Excel spreadsheet. In almost all such cases, acceleration or deceleration lanes were responsible for the apparent discrepancy, and the number of lanes corresponding to the basic freeway sections was selected.

If an XD segment is associated with a causal event for a specific timestamp, its parent link, parent corridor, and parent section are also associated with the same cause. In this hierarchical attribution of causes, primary incidents take precedence over incident impacts; i.e., if an XD-hour is associated with a primary incident and another XD in the same link for the same hour is associated with an incident impact, then the link is associated with the primary incident for that hour and not the incident impact as well. The same is the case with work zones.

## Data Quality Checks

Reasonableness of various data elements was checked both individually and with other data elements, and unreasonable values were dropped from further analyses in some cases. Average hourly confidence scores were obtained with the XD travel time data for basic verification of the data quality. A heatmap of percentage real-time data (i.e., confidence score = 30) for all XD segments, all hours, all days of the year, and all periods of the day was visualized. The road closure field was also obtained with the XD travel time data. The frequency of road closures was about 0.1% or less on most XD segments and was not considered significant enough to affect any analyses. XD travel times for all the timestamps associated with road closures were changed to an arbitrarily high value of 999 minutes so as to consider them in the high percentile group of unreliable travel times. Although this value itself is not meaningful, it gives a ready clue to the analyst that it was an artifact of coding and that visualizations should be zoomed in appropriately for the intended effects on decision making.

### Task 2. Calculation and Analysis of Travel Time Reliability Performance Measures

Two travel time reliability performance measures, PTI and LOTTR, were selected by the TRP for detailed exploration. Traditional methods of calculating these measures were available from the reviewed literature (Schrank et al., 2019; Taylor and Chang, 2017). Briefly, traditional PTI-80 is defined as the ratio of the 80th percentile travel time to the FFTT; LOTTR-80 is defined as the ratio of the 80th percentile travel time to the median travel time. A simple overview of the traditional and systemic corridor performance measure calculations is presented in Figure 5. Specific details of all the calculations for XD segments, links, corridors, and sections are presented in the subsections that follow.

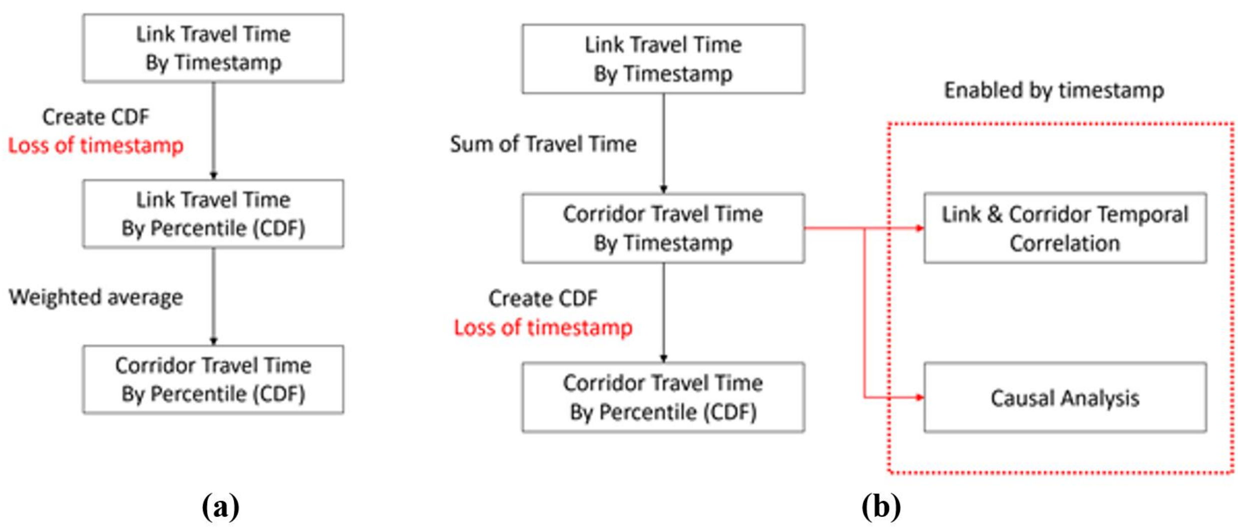



**Figure 5. Simple Overview of Corridor Travel Time Calculations by (a) Traditional and (b) Systemic Methods. CDF = cumulative distribution function.**

### FFTT for XD Segments

FFTT for an XD segment is its length divided by the free-flow speed (FFS). The literature frequently refers to FFS at a location as the 85th percentile speed from some time period when the traffic is low (Federal Highway Administration [FHWA], 2020; Schrank et al., 2015). Conversely, FFTT could be directly estimated as the 15th percentile travel time from the relevant travel time dataset. Schrank et al. (2015) used the nighttime hours of 2200 to 0459, and FHWA (2020) used the daytime hours of 0900 to 1559 and 1900 to 2159 for Monday through Friday and 0600 to 2159 on Saturday and Sunday. In this study, no major differences in FFS were found between using daytime or nighttime hours or by including or excluding the hours corresponding to known incident and work zone causes (see Figure 6). FFS was also calculated separately for each year of data and for all 4 years together. This showed some differences in the FFS values at some locations. However, no noticeable differences were observed in the calculated PTI values. Based on these findings, to reduce the computational burden, FFS could be calculated from the MAP-21 midday period without excluding any causes. This study calculated FFTT from the 4-year dataset after work zones and incidents were excluded and used the midday period.

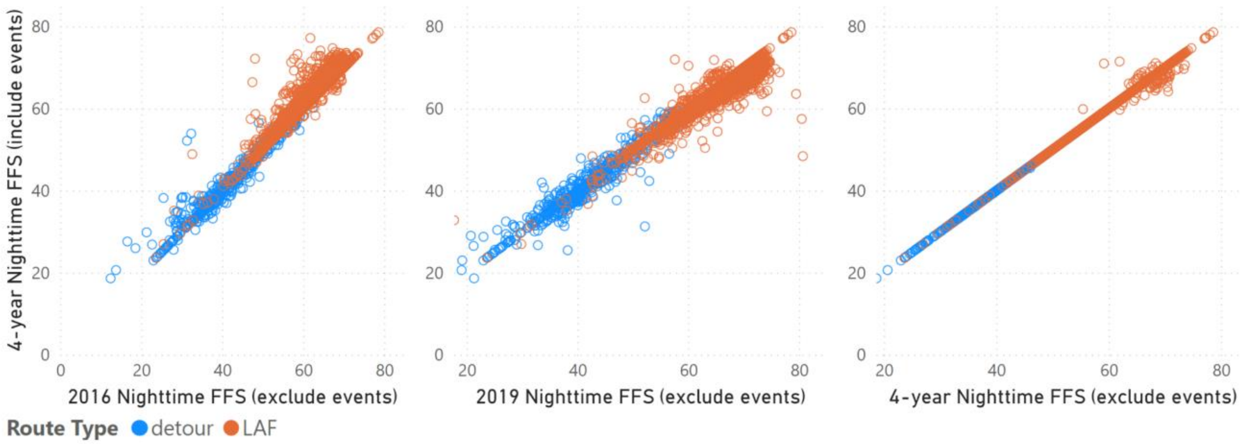
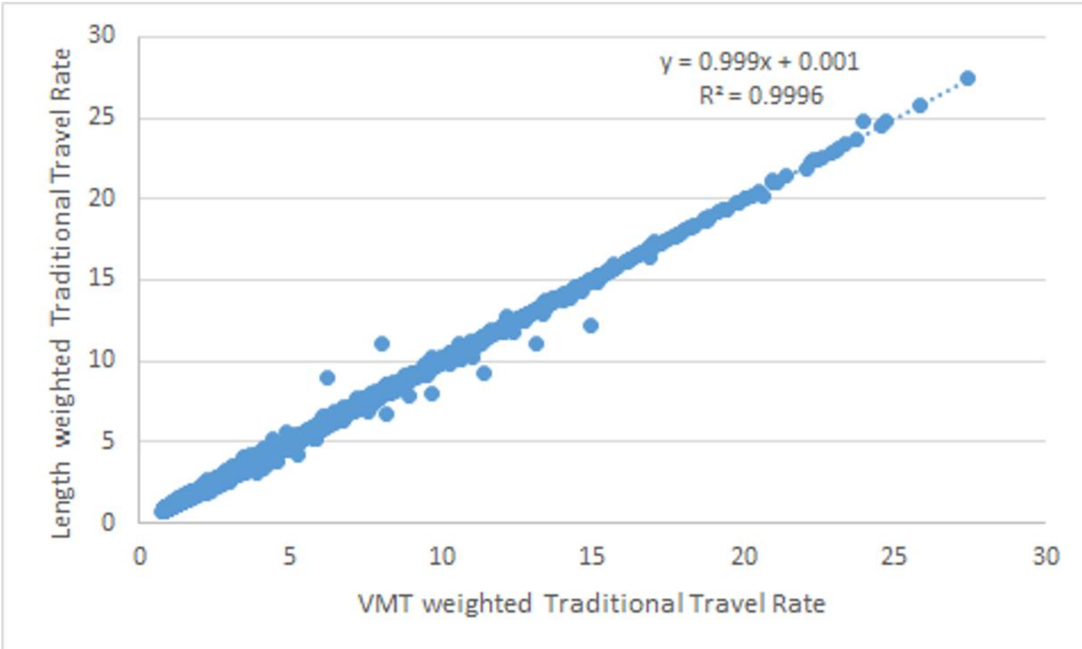



**Figure 6. Free-Flow Speed Scatter Plot With Include/Exclude Events and Multi / Single Year Comparison. FFS = free-flow speed; LAF = limited access facility.**

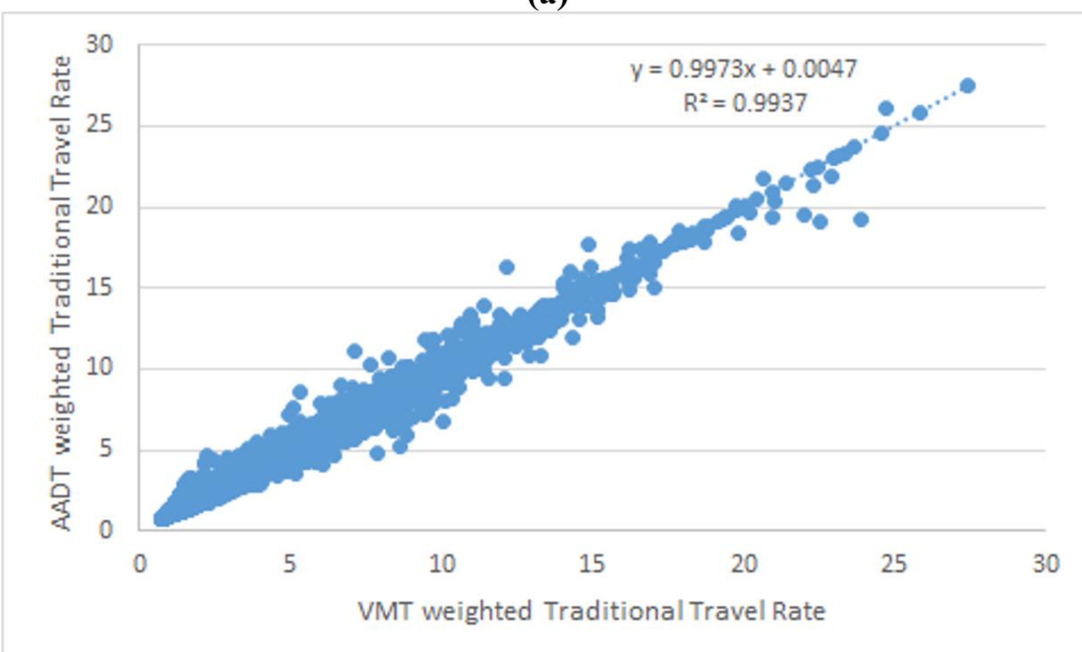
## Traditional PTI and LOTTR for XD Segments, Links, Corridors, and Sections

For each XD segment, year, and time period, median travel time was calculated. Historically, PTI and LOTTR are defined and used for only a few percentiles, such as PTI-80 and LOTTR-95. In this study, the PTI and LOTTR concepts were extended to all percentiles from 0 to 100. For example, PTI-60 of an XD segment for a given year and time period is defined as the ratio of the travel time at the 60th percentile to the FFTT. Further, PTI (at an XD segment) was extended to any travel time as the ratio of the given travel time to the FFTT. Similar extension can be performed with LOTTR. These extensions provided a normalized way of analyzing and comparing travel time cumulative distribution functions (CDFs) across different links and corridors using the PTI and LOTTR CDFs.

Traditional PTIs and LOTTRs for any timestamp and any higher spatial aggregation (such as link, corridor, and section) were, respectively, calculated as the weighted sum of the PTIs and LOTTRs of all the constituent XD segments. This same weighted sum approach was extended to calculate the traditional link travel time from the travel times of the constituent XD segments. Four different weights were tested in these calculations: hourly volumes, hourly VMTs, length, and AADT. As seen in Figure 7, no major differences in link travel rates were observed among these different weights. The normalized form of travel times by length (sometimes called travel rates) are shown in this visualization for ease of comparison across different link lengths. Both XD length and AADT have the significant advantage of not needing conflation of the hourly traffic volume factors. In this study, hourly VMT or volume was used as the weighting factor.




**(a)**




**(b)**

**Figure 7. Traditional Link Travel Rates Compared With Different Weights: (a) VMT vs. length; (b) VMT vs. AADT. VMT = vehicle miles traveled; AADT = annual average daily traffic.**

## Systemic Travel Time and Travel Rate for Links, Corridors, and Sections

For links, systemic travel time at a timestamp was calculated as the simple sum of the travel times of all the constituent XD segments at that timestamp. This value is often referred to as the instantaneous link travel time in the literature (Xiao et al., 2014). Since the total number of vehicles traversing a link at a given timestamp is the same across all the XD segments, the simple sum is the total travel time of a hypothetical vehicle traveling the entire link length. Systemic travel rate for a given link and timestamp is the ratio of the systemic link travel time to the link length.

Similar to links, corridor systemic travel time for each timestamp was calculated as the simple sum of the hourly average travel times of the corridor's constituent links, and corridor length was calculated as the simple sum of the lengths of all the corridor's constituent links. Corridor travel rate was calculated as the ratio of the corridor travel time to the corridor length.

For sections, the example schematic in Figure 8 with two LAF links and two detour links may be considered. The section LAF volume, length, and travel time using volume weights are calculated using Equations 1 through 3. Equations 4 and 5 are used to calculate section systemic travel time and length using volume weights.

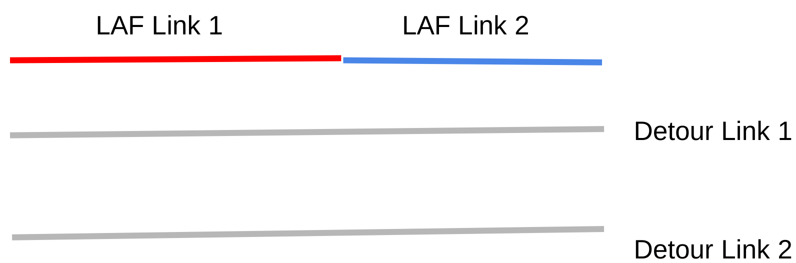



**Figure 8. Example Section With Two Limited Access Facility (LAF) Links and Two Detour Links**

$$Section\ LAF\ travel\ time = \sum_{l \in LAF} travel\ time_l \quad \text{[Eq. 1]}$$

$$Section\ LAF\ volume = \frac{\sum_{l \in LAF} volume_l \times length_l}{\sum_{l \in LAF} length_l} \quad \text{[Eq. 2]}$$

$$Section\ LAF\ length = \sum_{l \in LAF} length_l \quad \text{[Eq. 3]}$$

$$Section\ systemic\ travel\ time = \frac{\sum_{s \in LAF, Detour} volume_s \times travel\ time_s}{\sum_{s \in LAF, Detour} volume_s} \quad \text{[Eq. 4]}$$

$$Section\ systemic\ length = \frac{\sum_{s \in LAF, Detour} volume_s \times length_s}{\sum_{s \in LAF, Detour} volume_s} \quad \text{[Eq. 5]}$$

where

$l$ = link
$s$ = section component (either LAF or Detour).

In essence, the section systemic travel time is the total travel time of all the vehicles carried by the section (both LAF and Detour) divided by the total traffic volume carried by the section. The section systemic length is the total length traveled by all vehicles in the section divided by the total traffic volume carried by the section. The section systemic travel rate was calculated as the ratio of the section systemic travel time to the section systemic length.

**Systemic FFTT for Links, Corridors, and Sections**

Link FFTT was calculated directly from the link travel time data as the 15th percentile value from the midday period. Lan et al. (2020) calculated a network FFTT as the weighted sum of the FFTTs of the constituent links. Extending this approach to the sections will result in Equations 6 through 8.

$$Section\ LAF\ free\ flow\ travel\ time = \sum_{l \in LAF} free\ flow\ travel\ time_l \quad \text{[Eq. 6]}$$

$$Section\ LAF\ AADT = \frac{\sum_{l \in LAF} AADT_l \times length_l}{\sum_{l \in LAF} length_l} \quad \text{[Eq. 7]}$$

$$Section\ systemic\ free\ flow\ travel\ time = \frac{\sum_{s \in LAF, Detour} free\ flow\ travel\ time_s \times AADT_s}{\sum_{s \in LAF, Detour} AADT_s} \quad \text{[Eq. 8]}$$

where

*l* = link
*s* = section component (either LAF or Detour).

Using AADT as the weighting factor will ensure that the section systemic FFTT is consistent across different time periods.

As the spatial aggregation increases in size to corridors and networks, since the FFTTs of all the constituent individual links in a corridor or network may or may not occur at the same time, using a weighting method without considering the temporal factor may not be appropriate. Therefore, in this study, the corridor FFTT was calculated directly from the corridor systemic travel time as the 15th percentile corridor systemic travel time from the weekday midday periods. Similarly, section systemic FFTT was calculated as the 15th percentile section systemic travel time during the midday period.

**Systemic Median Travel Time for Links, Corridors, and Sections**

As with the systemic FFTT, the systemic median travel times for links, corridors, and sections were calculated directly from the systemic travel time values for the corresponding spatial aggregation and time period.

### Systemic PTI and LOTTR for Links, Corridors, and Sections

Once the systemic travel times, systemic FFTTs, and systemic median travel times are calculated, calculating the systemic PTI and LOTTR is straightforward, as indicated in Equations 9 and 10.

$$systemic\ PTI_t = \frac{systemic\ travel\ time_t}{systemic\ FFTT} \quad \text{[Eq. 9]}$$

$$systemic\ LOTTR_t = \frac{systemic\ travel\ time_t}{systemic\ median\ travel\ time} \quad \text{[Eq. 10]}$$

where

*t* = timestamp.

These calculations are simple to understand and use but cannot be directly extended to networks because volumes on different links in a network will be different and a simple sum of the travel times of all the links in a network is not meaningful. Therefore, an alternate calculation methodology applicable to both corridors and networks was developed as shown in Equations 11 and 12 (but not tested or used in this study):

$$systemic\ travel\ rate_{cn,t} = \frac{\sum_{l \in cn} volume_{l,t} \times systemic\ travel\ time_{l,t}}{\sum_{l \in cn} volume_{l,t} \times length_l} \quad \text{[Eq. 11]}$$

$$systemic\ free\ flow\ travel\ rate_{cn} = 15th\ percentile\ systemic\ travel\ rate\ during\ midday\ period \quad \text{[Eq. 12]}$$

where

*cn* = corridor or network
*l* = link
*t* = timestamp.

Equations 9 and 10 can be used with the travel rates.

### Hardware and Software Tools for Computing Measures

The XD travel time data in .csv files for 4 years were more than 30 GB in size. Given the large dataset sizes, a general purpose, open-source programming language (Python) was used for calculating the performance measures. Even 1 year's worth of data could not be loaded and joined with other necessary files on a VDOT laptop computer with 16GB of RAM, Intel i7 CPU, and a 237 GB hard disk drive. Therefore, cloud computing resources were employed. Initial coding and computations were carried out on the Rivanna high performance computing servers at the University of Virginia. Final coding and computations were performed on VDOT's cloud computing platform that uses Microsoft Azure for data storage and Databricks for computation. Each instance spun on Databricks had two to four worker nodes with 512 GB RAM and 64 cores each. The computations were vectorized and optimized to the extent feasible within the time schedule of this study and took about 30 to 45 minutes to complete for the entire study area for 4 years of data for generating link and section files. Calculating corridor measures took an additional 20 to 30 minutes. Future updates to the code to take advantage of parallel, big data computing can potentially reduce the compute time and hardware resources needed.

Even though Python was the main coding language used, Databricks uses Spark to connect to Azure to read and write files. Technical details such as converting between Python and Spark dataframes, ensuring that appropriate data time formats are used in the analyses, etc., are included in the Python code files.

**Analyses of Performance Measures**

The following six specific analyses were carried out:

1. analysis of link travel times by traditional and systemic approaches
2. analysis of link travel time reliability by traditional and systemic approaches
3. exploration of section systemic travel times
4. analysis of section travel time reliability by traditional and systemic approaches
5. exploration of spatial context to identify unreliable travel time links
6. exploration of spatiotemporal context to identify unreliable travel time links.

For the first three analyses, the impacts of five available underlying traffic and geometric factors, namely, AADT, number of lanes, AADT per lane, truck percentage, and link length, were also studied. Power BI was extensively used for visualizing the results, evaluating the calculations, and analyzing and presenting the final results to the TRP and the AP. Tableau, Excel, and Python were also used in some intermittent steps.

## Task 3. Design and Application of Systemic Screening Methodology

Exploiting the spatiotemporal context of link unreliability developed in the previous task, this study explored a new method to screen and rank links that are highly correlated with (and hence show the potential to improve) corridor travel time unreliability. This methodology also helps identify upstream-downstream links within a corridor that are concurrently unreliable. The proposed method can be translated into the following three selection rules:

1. Identify links that are more unreliable than the corridor.
2. Identify links that are unreliable when the corridor is unreliable.
3. Determine threshold minimum link and corridor reliability measures.

Figure 9 demonstrates these selection rules for an example corridor. The base data for the network screening are the combined link and corridor PTI values matched by timestamps, as shown in Figure 9(a). Figure 9(b) shows the results of applying the first selection rule to the base data. It was observed empirically that the corridor PTI had a smaller range relative to the link PTIs. In Figure 9(a), individual link PTIs go as high as 9, 11, or even 13 whereas their maximum corridor PTI is around 4.5. This was likely due to the balancing of highly unreliable travel times at one link by relatively more reliable travel times at other links at any given time stamp. The first rule helps to screen out all the links that are more reliable than the corridor itself and hence are less likely to be causing the corridor unreliability. It is noted that corridors with one link will be screened out by this rule by design, even if highly unreliable, and need to be studied separately.

The second selection rule keeps only the data points where both link and corridor PTI values are in their top 20 percentiles (see Figure 9[c]), which represents the number of timestamps (hours) that both the link and the corridor are unreliable. PTI-80, representing the top 20 percentile unreliable travel time situations, is commonly considered in operational analyses and was used as the reliability threshold for selection rule 2. This rule essentially screens out all the hours when either the link or the corridor is reliable (also when both are reliable), as they are not of primary value to identifying causes of corridor unreliability.

The third rule ensures that highly reliable links and corridors meeting the first two rules (say, with a link PTI of 1.0 and a corridor PTI of 1.03) are not prioritized in the screening. In this study, a link PTI threshold of 1.5 and a corridor PTI threshold of 1.2 were used as proof-of-concept examples, noting that different threshold values may be appropriate for different use cases. In other words, all data points with a link PTI less than 1.5 and/or a corridor PTI less than 1.2 were excluded from the analysis. A slightly lower corridor PTI threshold compared to the link PTI threshold was used due to the empirical observation presented earlier. It was also noted empirically that a high link PTI threshold value, say, 3.0, will effectively keep only highly unreliable hotspot links, and the results may be similar to those of the traditional screening method. Further, a high corridor PTI threshold value, say, 3.0, will effectively screen out many rural corridors. Therefore, a suitable balance between these extreme values needs to be sought based on the use case under consideration.

Once these three rules are applied, the number of hours when both a link and its corridor are unreliable (i.e., the number of data points in Figure 9[c]) is used to quantify the combined, correlated link-corridor unreliability. Since the link-corridor combined unreliability is captured by the worst 20 percentile travel times in both the link and the corridor, this network screening method is referred to as the “Top 20-20 method.” An important, inherent feature of the method is the consideration of both the magnitude and the frequency of the link-corridor combined unreliability. Rather than depending on just one point of data, such as PTI-80, this method considers all the points above the 80th percentile line for both the link and its parent corridor. The “Top 20-20 hours” provides an indication of which links to monitor and address in order to improve their parent corridor’s reliability. Two upstream-downstream links that are concurrently unreliable can also be identified to determine further if they both need to be improved together in order to improve the corridor effectively.

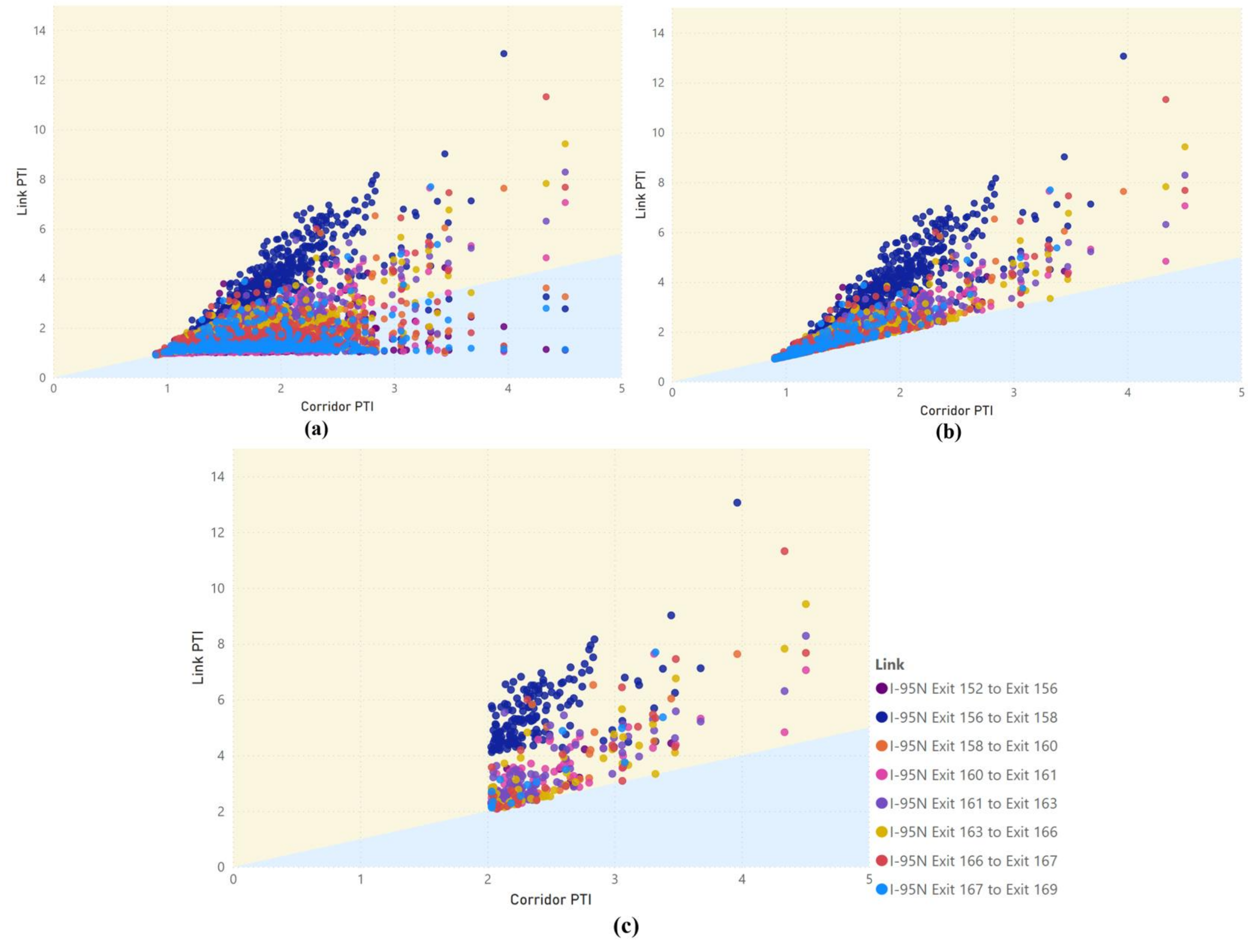



**Figure 9. Example Application of the Selection Rules of the Top 20-20 Network Screening Method: (a) base data; (b) results after applying selection rule 1; (c) results after applying selection rule 2. PTI = planning time index.**

Although the top 20% unreliable link PTI values and top 20% unreliable corridor PTI values were studied and are presented in this report, other percentage cut-off points such as "Top 5-5" (to represent 95th percentile link and corridor PTI values), "Top 30-20" (to represent the 70th percentile link PTI values and the 80th percentile corridor PTI values), etc., may be more meaningful for specific use cases. Although PTI is used here for illustrative purposes, LOTTR and other reliability measures can also be used.

By design, some links within any corridor will have PTI values above the 45-degree line, and some links will have PTI values below the 45-degree line. This relative distribution does not necessarily mean that the second set of links does not have any reliability problems. Instead, the purpose of the Top 20-20 method is to identify highly unreliable corridors and the highly unreliable links within these corridors that are concurrently unreliable with their parent corridor. Once these two lists are identified, more analysis and review are needed to identify appropriate solutions. Further, the Top 20-20 method may not always identify (1) unreliable hotspots at interchanges where the traffic diverts to or comes from another corridor, and (2) unreliable corridors that contain only one link, as screening rule 1 will remove all the points on the 45-degree line. For these situations, the traditional method is still very useful.

As with the analyses of the performance measures, Power BI was extensively used for visualizing the results, evaluating the calculations, and analyzing and presenting the final results to the TRP. All the link-corridor pairs in the study network were studied in detail for the 2019 AM peak period and selectively studied for other years and time periods.

### Task 4. Combined Causal Analysis of Links and Corridors

Using the timestamps and the associated events from the systemic travel time reliability analysis, link- and corridor-level causes of congestion were first identified. Even though four types of traditional congestion causes, namely, incidents, work zones, weather events, and holidays, were included in this study, this analysis may be more accurately described as the correlation of link and corridor timestamps with known congestion-causing events. The events correlation analysis is particularly useful in conjunction with the screening methodology and with the upstream-downstream unreliable links.

### Task 5. Validation of Results

The research team met periodically with the TRP and the AP to present progress updates and intermediate/final results. Power BI visualizations allowed for the drill down of the measures, factors, screening results, and causes. Qualitative feedback from the TRP and the AP was recorded from each meeting and incorporated into the next steps of the study. Given the exploratory nature of this study and the lack of directly comparable traditional methods, the panel feedback and the identified use cases were used toward qualitative validation of the soundness of the methodology and the usefulness of the results to VDOT business units.

## RESULTS AND DISCUSSION

### Data Collection and Preprocessing

#### Data Quality Checks

Percentage of real-time data for all XD segments in the study area, by date and hour in the 2019 AM peak period, is shown in Figure 10. As expected, data quality was generally better during the daytime, on weekdays, and on highly travelled roads and improved over the years. Figure 11 shows an example map of the percentage of real-time data (i.e., the confidence score 30 column from the XD database) in the westbound and southbound XD segments in the study network for the AM peak period in 2019. The percentage of real-time (confidence score 30) XD segment data on arterials was about 65.9%, compared to 99.4% on the LAFs. The marked improvement observed in data quality around June 2019 corresponds with a documented increase in probe vehicles by INRIX (Salerno, 2020).

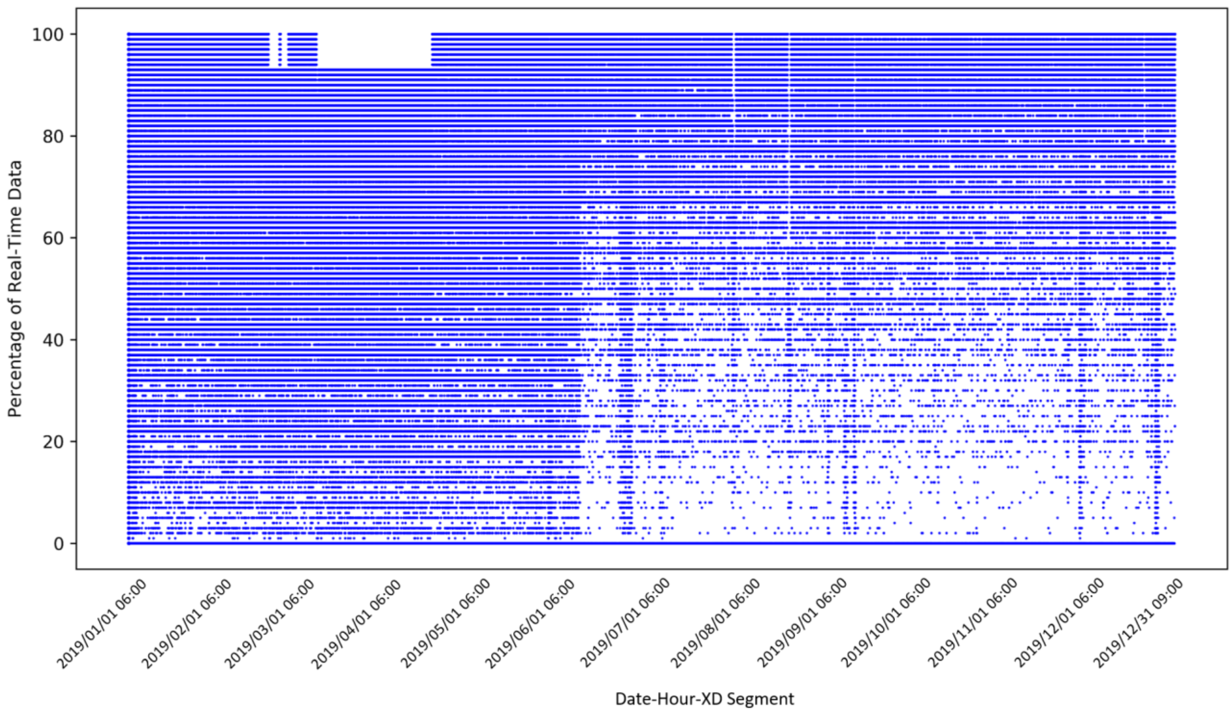



**Figure 10. Example Heatmap of XD Segment Data Quality for the 2019 AM Peak Period**

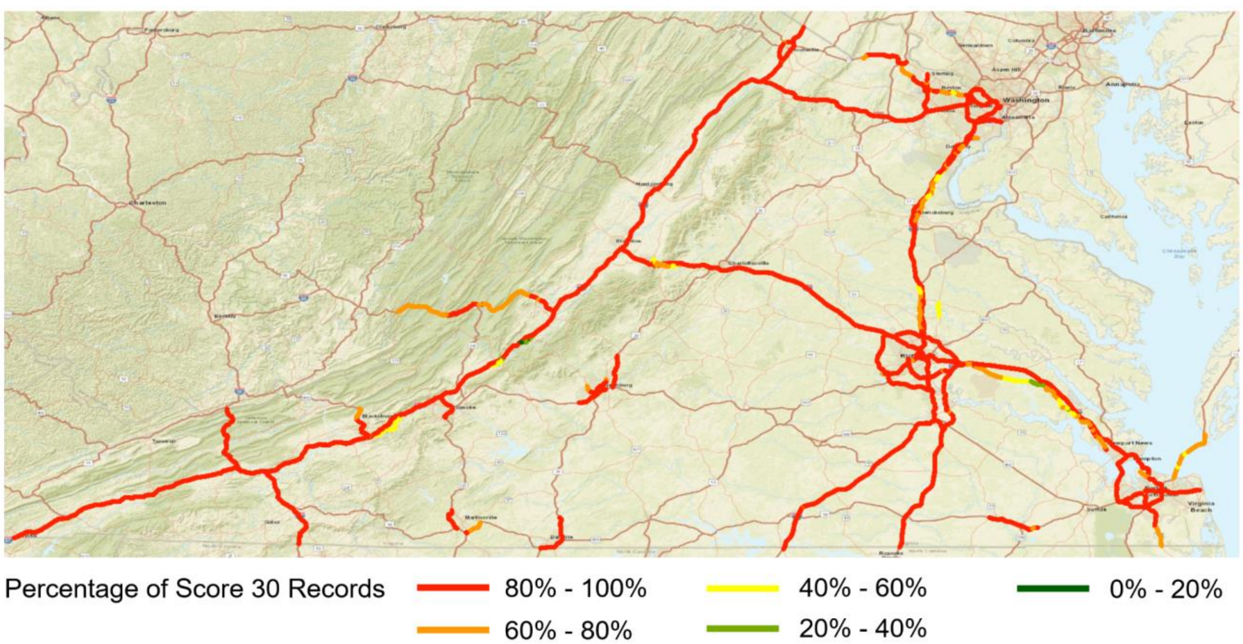



**Figure 11. Example Map of Percentage of Southbound and Westbound XD Segment Records With Confidence Score 30 in the 2019 AM Peak Period**

## Analysis of Link Travel Times by Traditional and Systemic Approaches

Link travel times are the simplest possible measure of comparison between the traditional and the systemic approaches, focusing exclusively on the difference between summing the XD segment travel times by timestamps or by percentiles. To enable an "apples-to-apples" comparison, the timestamped systemic link travel times were also converted to percentiles. Figure 12 shows an example comparison of the traditional to systemic travel times on an arterial link in the 2019 PM peak period. This graph is representative of the general trend for all the arterials. A value of 1 on the X-axis means the two values are equal. Points to the right of this vertical line correspond to percentiles when the traditional travel time is higher than the systemic travel time and vice versa. The traditional link travel times were higher than the systemic travel times at the higher percentiles and vice versa at the lower percentiles. This observation is in line with the original expectation and network-level observations by Lan et al. (2019).

The same comparison for the LAF links showed several other variations, especially at the higher percentiles, as seen in Figure 13. All these variations are quite explainable. In essence, the same XD segment travel times in the underlying dataset are simply combined in different ways to obtain the link traditional and systemic travel times. Any overestimation by one approach at a percentile is simply compensated for by some underestimation at another percentile, and although some variations are noticeable, others are subtle and small. These graphs simply highlight different possible relative over- or underestimations by an approach at any given percentile.

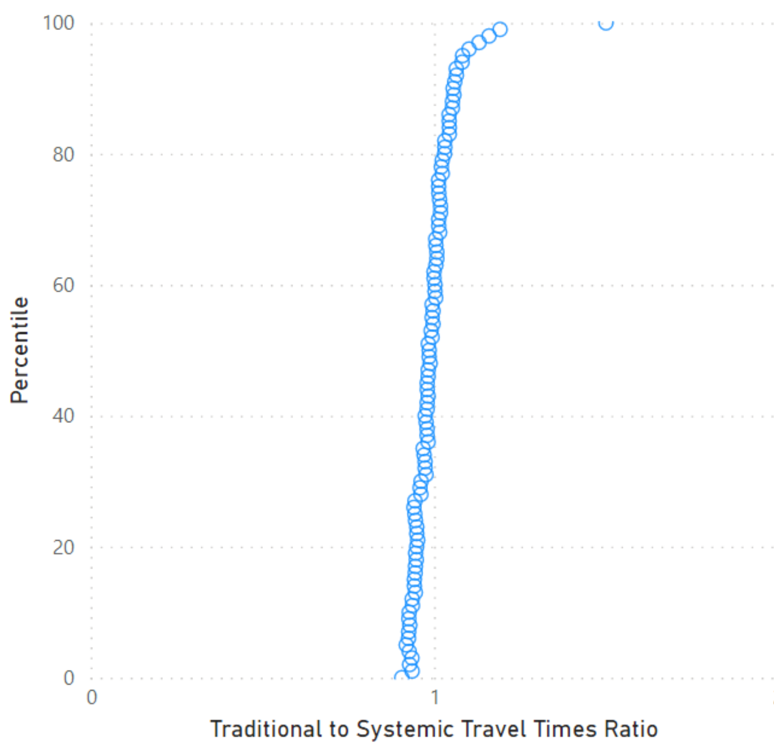



**Figure 12. Example Comparison of Traditional and Systemic Travel Times for an Arterial Link (US-1 Parallel to I-95N Exit 84 to Exit 86) in the 2019 PM Peak Period**

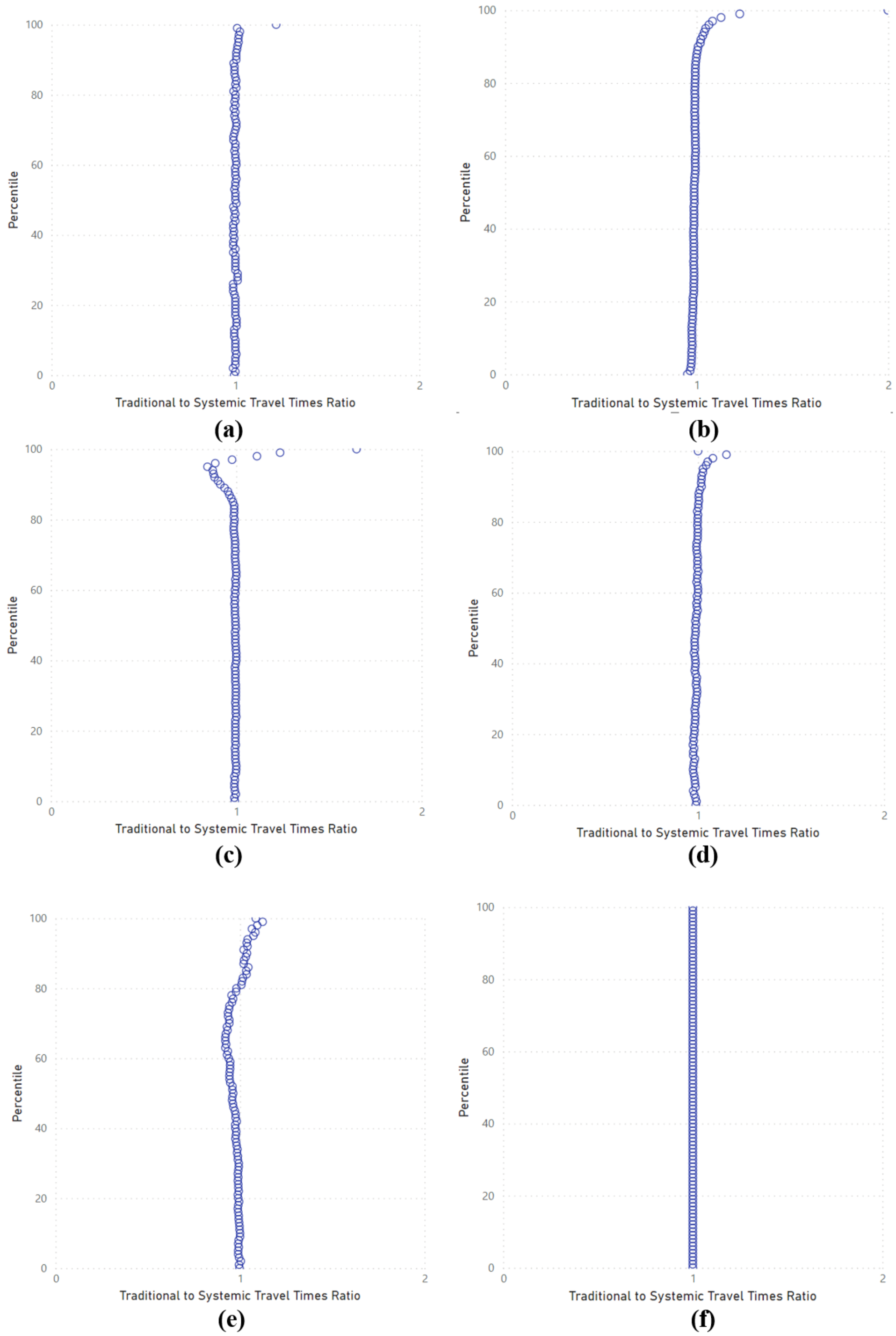



**Figure 13. Example Comparisons of Traditional and Systemic Travel Times in 2019 for Limited Access Facility Links: (a) I-66E Exit 69 to Exit 71 in AM peak; (b) Chesapeake Bay Bridge Tunnel (US13) NB in AM peak; (c) George Washington Memorial Parkway at SB Spout Run Parkway in midday period; (d) I-64E Exit 268 to Exit 272 in AM peak; (e) George Washington Memorial Parkway at SB Spout Run Parkway in AM peak; (f) Harry Byrd Highway (VA7) EB-VA-267-Dulles Greenway in AM peak.**

Observations regarding the higher percentile unreliable travel times from Figure 13 are of particular interest to this study. Figure 13(a) shows a situation where only the 100th percentile value is noticeably different between the two approaches. Figure 13(b) closely resembles the initially expected behavior observed in Figure 12, with the traditional travel time higher than the systemic travel time at higher percentiles, and vice versa at the lower percentiles. In Figure 13(c), the addition of high XD travel times between the 98th and100th percentiles in the traditional approach is closely followed by the compensation in the next few percentiles, around the 85th to 97th percentiles. In Figure 13(d), the 100th percentile travel times by the two approaches are similar. However, for some 10 percentile points or so, the traditional travel time is higher than the systemic travel time. The compensations are less dramatic and spread out over the remaining percentiles. Figure 13(e) highlights a situation where the traditional travel time is higher than the systemic travel time between the 80th to 100th percentiles, followed by a reverse relationship between around the 40th to 80th percentiles. At other percentiles, the two approaches yielded similar results. Figure 13(f) shows a situation where a link contains only one XD segment and therefore shows no difference between the two approaches, which is also possible when multiple XD segments in a link all have congestion or free-flow traffic regimes concurrently.

The primary reason suspected for the observed uniformity in the systemic vs. traditional travel times for the arterial links as compared to the LAF links is the inherently high randomness in travel times from one XD segment to another on the arterials due to factors such as changes in traffic volumes, traffic control (such as signals, roundabouts, signal timing changes, signal preemption etc.), and midblock accesses. Whereas the systemic method evens out the randomness from one timestamp to another, the traditional method considers all high travel times together and all low travel times together, stretching out/in the higher and lower percentile values. However, this hypothesis could not be conclusively validated due to the lack of pertinent data and the relatively few arterial links (73) studied in this project compared to the 1,125 LAF links. Further, beyond the rational understanding of the observed LAF variations, it is noted that the ratio of systemic to traditional travel times is often quite close to unity, i.e., these observed variations may be only symbolic and may not mean much practically. This observation is also in line with the earlier findings of List et al. (2014) for interstates.

The relationship between the link systemic and traditional travel times was analyzed in the light of five available underlying traffic and geometric factors. One such graph with the truck percentage is shown in Figure 14. No strong correlations or patterns were observed between any of these factors individually. However, interactions among these and other factors may be of interest for future research, as identified by Zhang et al. (2021).

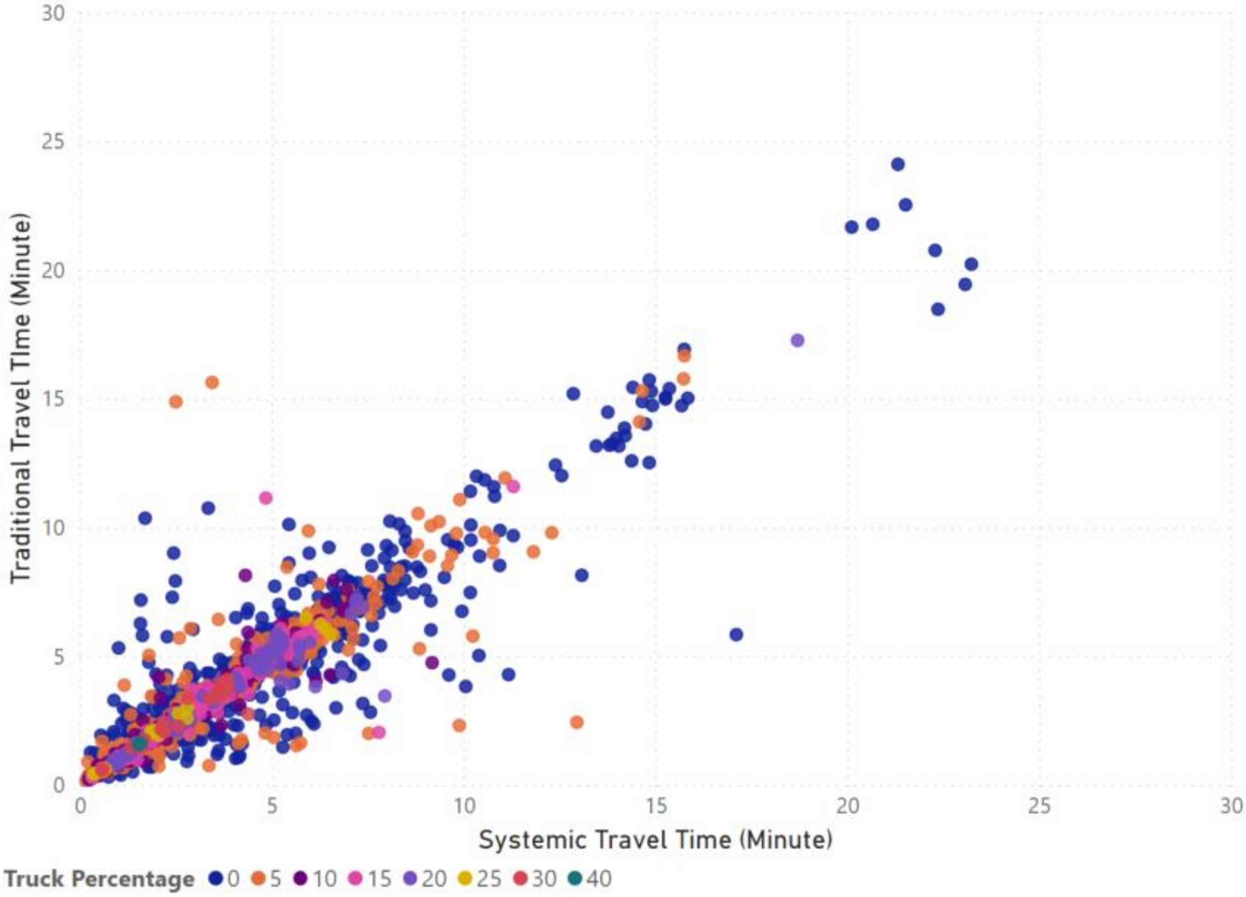



**Figure 14. Analysis of Link Systemic vs. Traditional Travel Times With Truck Percentage**

## Analysis of Link Travel Time Reliability by Traditional and Systemic Approaches

Almost all the links had similar PTI CDFs by both methods, as shown in Figure 15(a). Some links showed some variations, as seen in Figures 15(b) and (c). Both these links are on arterial routes and mirrored similar variations in link travel time CDFs by the two calculation approaches. Whereas Figure 15(b) shows higher PTI with the traditional method at higher percentiles, and vice versa at lower percentiles in comparison to the systemic method, Figure 15(c) shows higher PTI with the traditional method for all percentiles. The main reason suspected for this variation is the impact of the FFS (or FFTT) on PTI. Even small variations in the denominator can cause a large change in the PTI, and a link FFTT is not expected to have any explainable relationship with the underlying XD FFTTs.

Link LOTTR CDFs by the traditional and the systemic approaches showed trends similar to those for the link PTI CDFs (see Figure 16 for examples). It is noted that the 50th percentile LOTTR values by both methods are observed empirically to meet near 1, since the 50th percentile travel time serves as the denominator for LOTTR calculations.

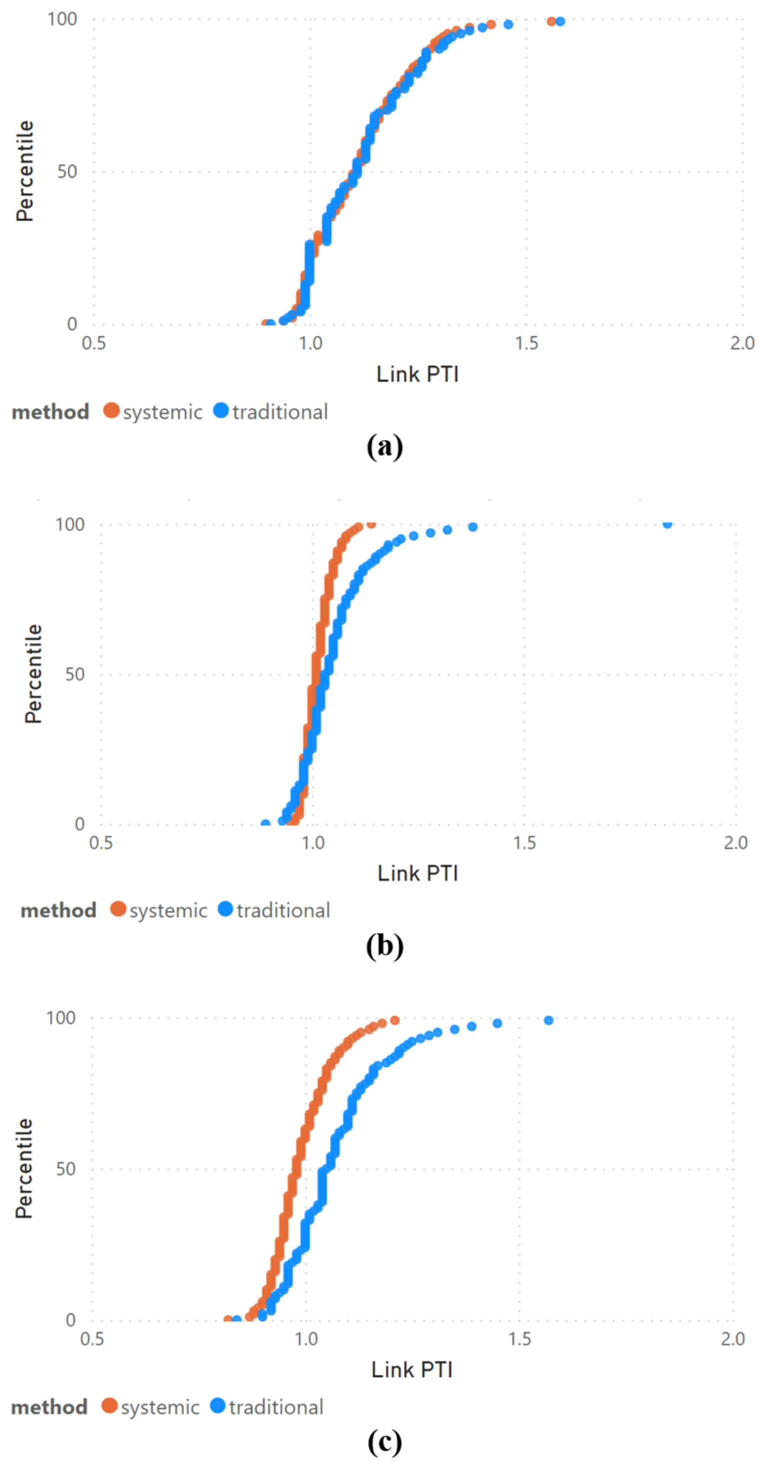
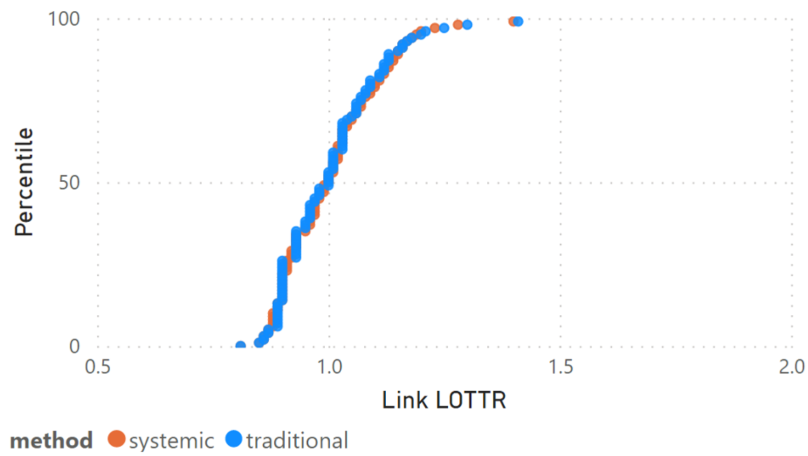
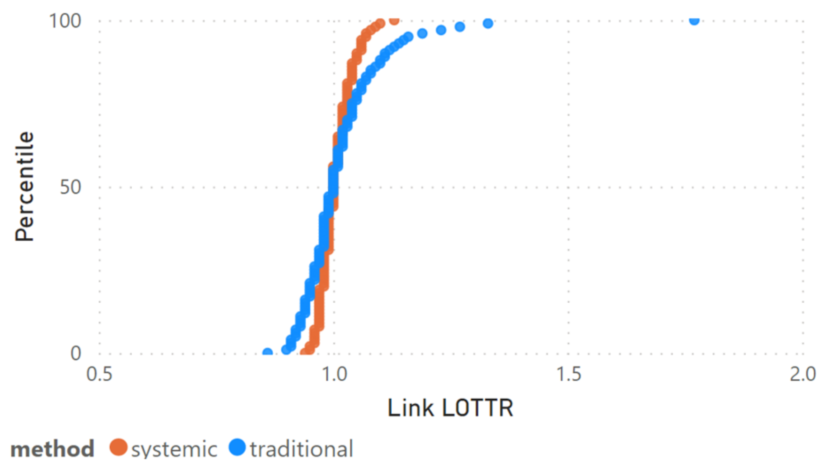



**Figure 15. Systemic vs. Traditional Planning Time Index Cumulative Distribution Functions From the 2019 AM Peak Periods for Three Example Links: (a) I-66E Exit 69 to Exit 71; (b) US-11_I-81S Exit 168 to Exit 175; (c) US-1_I-95N Exit 84 to Exit 86. PTI = planning time index.**




**(a)**

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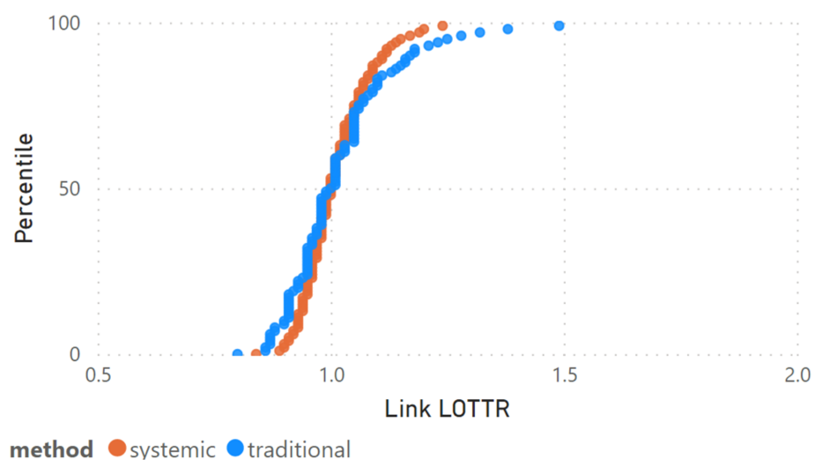



**(c)**

**Figure 16. Systemic vs. Traditional Level of Travel Time Reliability (LOTTR) Cumulative Distribution Functions From 2019 AM Peak Periods for Three Example Links: (a) I-66E Exit 69 to Exit 71; (b) US-11_I-81S Exit 168 to Exit 175; (c) US-1_I-95N Exit 84 to Exit 86.**

The high similarity observed in both link PTIs and LOTTRs from the traditional and the systemic methods means that the less computationally burdensome traditional method can continue to be used for all link-level analyses with higher confidence, especially on LAFs, unless timestamps from the systemic method provide additional value, such as the enablement of causal analyses, or arterial routes are of special interest. The observed high similarity will also likely help practitioners to gain more confidence in using the new systemic method.

### Exploration of Section Systemic Travel Times

Systemic analyses of sections provided a unique new opportunity to juxtapose the travel time CDFs of the sections, their interstate parts, and their detour route parts together. Figure 17 shows these graphs for two example sections.

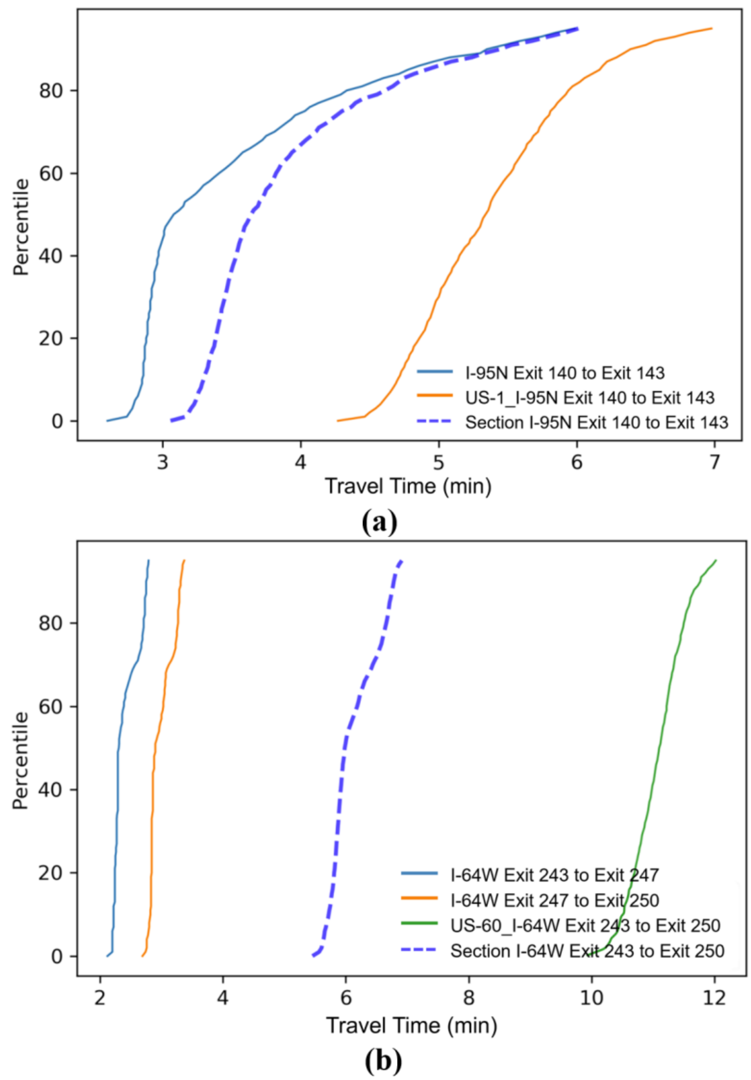
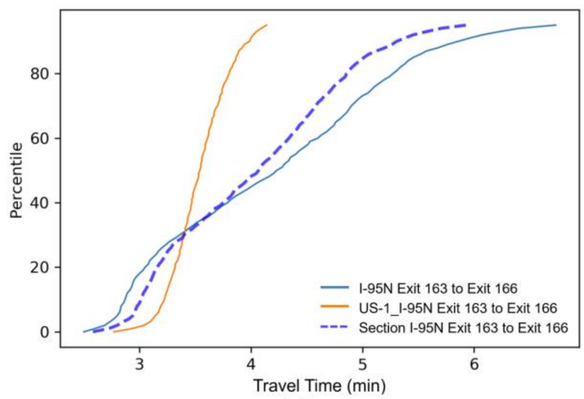


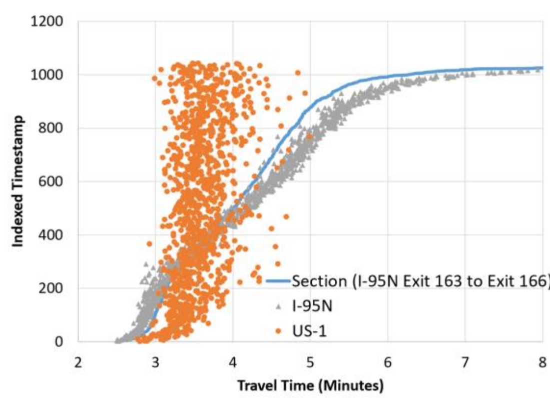

**Figure 17. Systemic Travel Time Cumulative Distribution Functions From the 2019 AM Peak Period for Two Example Sections: (a) I-95N Exit 140 to Exit 143; (b) I-64W Exit 243 to Exit 250.**

In general, as in both of these examples, the interstate links are faster than their arterial counterparts. In Figure 17(a), the arterial link travel time CDF is more vertical and hence more reliable than the interstate link. However, only the parallel arterial links and not the connecting ramps or routes were considered in this study. Once those route elements are added, it is possible that the arterial route may not be as reliable as this figure shows. Both graphs also show that the interstate links have a strong impact on the section systemic travel time CDF (dashed blue lines), likely due to the high traffic volumes carried by the interstate, and hence their higher weights in the section calculations.

Figure 18 shows a different example of section travel times with corresponding interstate and detour parts. Figure 18(a) shows a situation where the travel times and the reliability seem better on the detour route than on the interstate route. However, these CDFs all show monotonically increasing travel times by percentiles, by definition, and the actual travel times at each timestamp on the different routes are not visible. Figure 18(b) further exploits the timestamped travel time information available for sections from the systemic analysis. In this graph, the Y-axis represents the timestamps arranged by the increasing order of section systemic travel times. Therefore, the section systemic travel time curve (in blue) in Figure 18(b) closely mimics the section travel time CDF shown in Figure 18(a).




**(a)**




**(b)**

**Figure 18. From the 2019 AM Peak Period for Section I-95N Exit 163 to Exit 166: (a) section, interstate, and detour systemic travel time cumulative distribution functions; (b) systemic section travel time cumulative distribution function juxtaposed with timestamped interstate and arterial travel times.**

However, the interstate and detour travel times shown in Figure 18(b) correspond to the actual timestamps on the Y-axis. In this view also, the arterial travel times are generally faster and more reliable than the interstate route, and the underlying variability is also noticeable.

Figure 19 shows a different way of comparing the interstate and detour route travel rates of a section, with the 45-degree line marked (in green). Although travel rates are used here for a length-normalized comparison of the travel times on different routes, the detour lengths are often higher than the interstate route, especially after the connecting route lengths and ramps are added (which were not considered here). It was observed that the travel rates (and travel times) on interstate and detour links of a section are usually not highly correlated, even when incidents occur on the interstate. Two main reasons suspected for this observation are (1) the gating effect provided by the signal controls, and (2) real-time operational updates of the signal timings to accommodate higher detoured traffic.

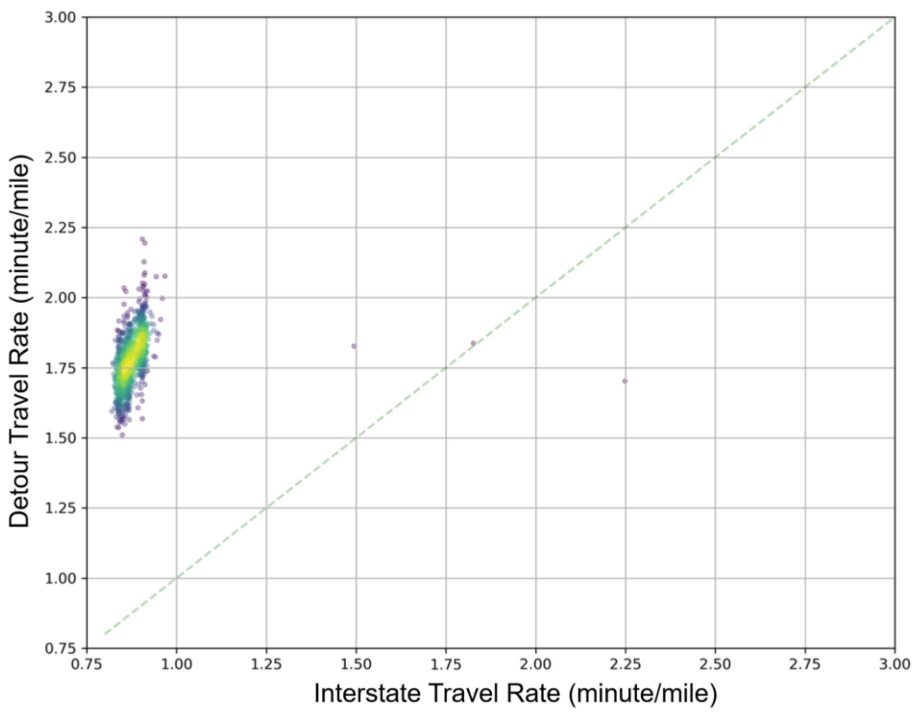



**Figure 19. Density Scatter Plot of Interstate and Detour Travel Rates for the Section I-64E Exit 250 to Exit 255 for the 2019 AM Peak Period. Purple to green to yellow represents increasing density of points.**

## Analysis of Section Reliability by Traditional and Systemic Approaches

Figures 20 and 21, respectively, show that the relative shapes of the systemic and traditional PTI CDFs and LOTTR CDFs for sections display more variations compared to the LAF links, but there is a lot of similarity between the two measures themselves. With relatively shorter overall lengths covered by sections compared to networks, and several more factors at play compared to LAF links, these variations between the two methods in the sections are not easy to explain fully. However, the fact that these two are still comparable to some extent is likely to give more confidence for the field practitioners to use the systematic approach in place of the traditional approach, with the added advantage of juxtaposing interstate CDFs with detour routes and for performing timestamp-based causal analyses for sections.

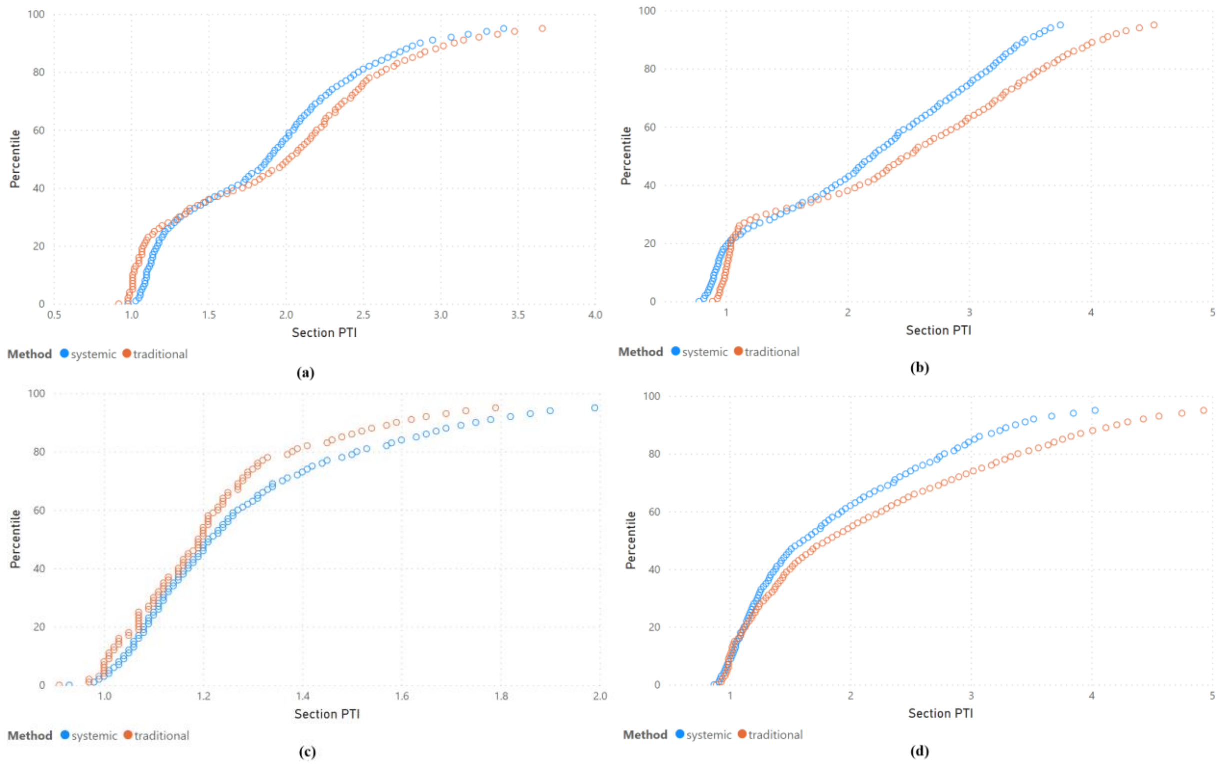



**Figure 20. Systemic and Traditional Planning Time Index (PTI) Cumulative Distribution Functions in 2019: (a) I-95S Exit 160 to Exit 161 during midday; (b) I-95S Exit 160 to Exit 161 during weekend; (c) I-95S Exit 158 to Exit 160 during midday; (d) I-95N Exit 156 to Exit 158 during AM peak period.**

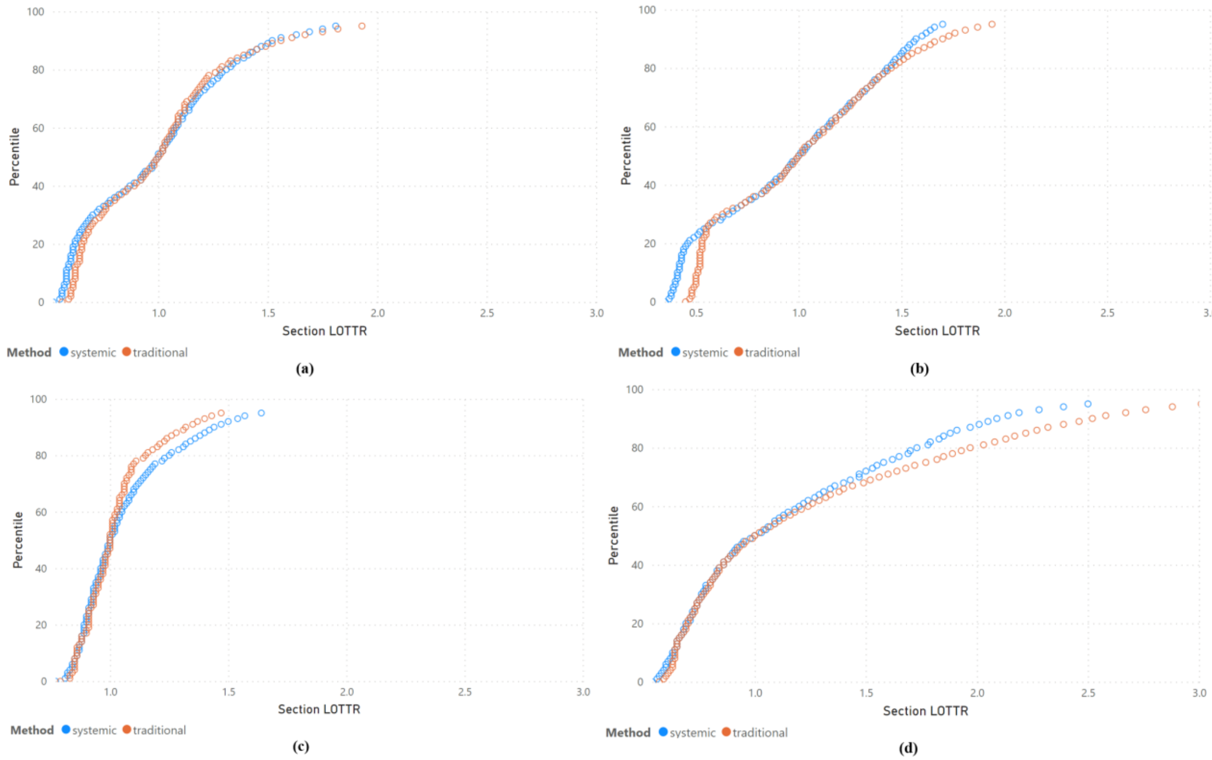



**Figure 21. Systemic and Traditional Level of Travel Time Reliability (LOTTR) Cumulative Distribution Functions in 2019: (a) I-95S Exit 160 to Exit 161 during midday; (b) I-95S Exit 160 to Exit 161 during weekend; (c) I-95S Exit 158 to Exit 160 during midday; (d) I-95N Exit 156 to Exit 158 during AM peak period.**

## Exploration of Spatial Context With Traditional Reliability Measures to Identify Unreliable Links

Using the approach explained earlier, the 73-mile stretch of I-66 Eastbound in the study area was divided into four corridors: Inside the Beltway (from I-495 Capital Beltway to the Washington, D.C., border), I-495 Capital Beltway to US-28, Rest of the Fairfax County, and Fauquier County (see Figure 22).

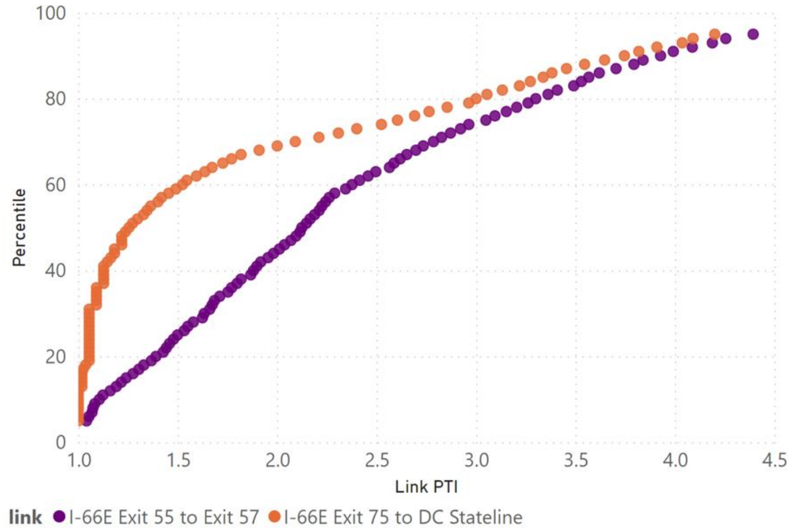

**Figure 22. Four Corridors Defined Along I-66 Eastbound. Each link is represented by its midpoint, and each corridor by a color.**

Figure 23(a) shows the traditional PTI CDFs for two links: I-66E Exit 55 to Exit 57, and I-66E Exit 75 to DC Stateline. These links are located, respectively, on the I-495 Capital Beltway to US-28 corridor and the Inside the Beltway corridor. Since these two links have similar PTI values across all the higher percentiles, the traditional network screening methodology looking at PTI-95 or PTI-80 will rank these two links similarly. Notably, these two links are located on different corridors with different PTI CDFs (see Figure 23[b]). For all four I-66 Eastbound corridors, Figure 23(c) compares the link PTI values (on the y-axis) to its parent corridor PTI values (on the x-axis) at each percentile. There are 101 points (0th to 100th percentiles) for each link-corridor pair. Each link is represented by a different color, and each corridor is represented by a different shape of the data points. Each vertical slice in this figure corresponds to a specific percentile value for one corridor. The intersection of the yellow-blue shaded areas represents the 45-degree line where the link and the corridor PTI values are equal. Compared to the traditional link-based analysis, the link-corridor analysis recognizes the link located on a more unreliable corridor by contrasting the link performance with the corridor performance. Further, all four possible combinations of link-corridor reliability, namely, link and corridor both being reliable or unreliable and either of them being reliable while the other one is unreliable, were observed in the study network and can be seen in Figure 23(c).

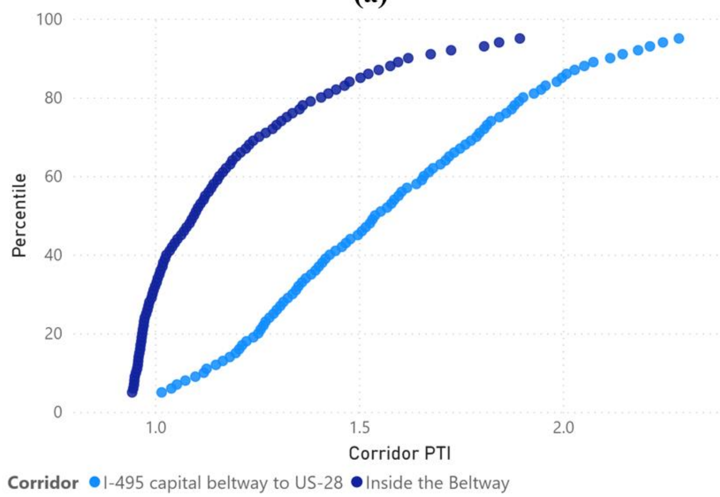
Figure 24(a) shows the year-to-year comparison of the PTI CDFs of a link, all of which look similar. However, Figure 24(b) reveals that the corridor containing this link deteriorated in performance from 2016 to 2017 to 2018 and slightly improved from 2018 to 2019. The corresponding corridor PTI-95 values were around 1.95, 2.15, 2.3, and 2.25, respectively.

This link-corridor analysis provides a new spatial context for screening links in a network, with an added emphasis on reliability at the corridor level rather than just at individual links. Since unreliable links in a network may not necessarily be located always on unreliable corridors, ranking unreliable links independently vs. considering link-corridor relationships may yield different results. Performing this link-corridor analysis requires minimal updates to the traditional approach.

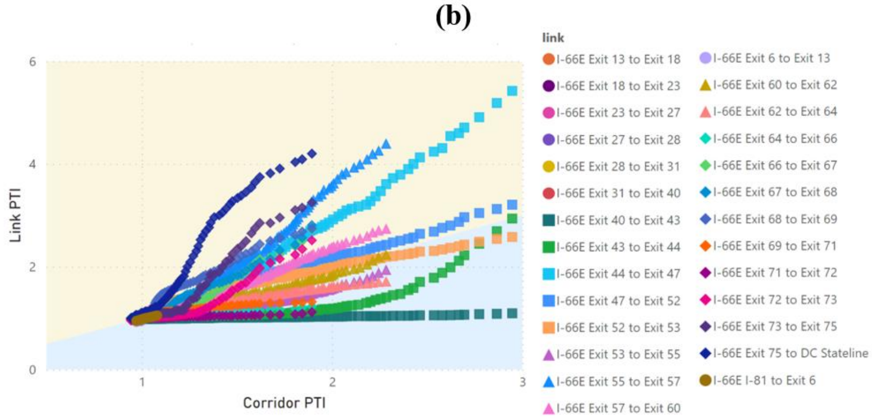
However, this analysis also suffers from one significant drawback. When looked at independently, by definition, PTI CDFs of both the link and its parent corridor will always increase monotonically. However, the unreliable travel time situations on links and their parent corridors may or may not be concurrent. The lack of timestamp information in the traditional CDF-based analyses overlooks the temporal context of the reliability problem. In other words, all four combinations of link-corridor relative reliability or unreliability are possible at any given timestamp. There may be timestamps when a link is relatively unreliable but the corridor is relatively reliable or vice-versa and timestamps when both a link and its corridor are relatively reliable or unreliable. In order to understand better and improve the reliability of a corridor, there is a need to identify links that are highly correlated with corridor unreliability using both the spatial and the temporal contexts.




**(a)**

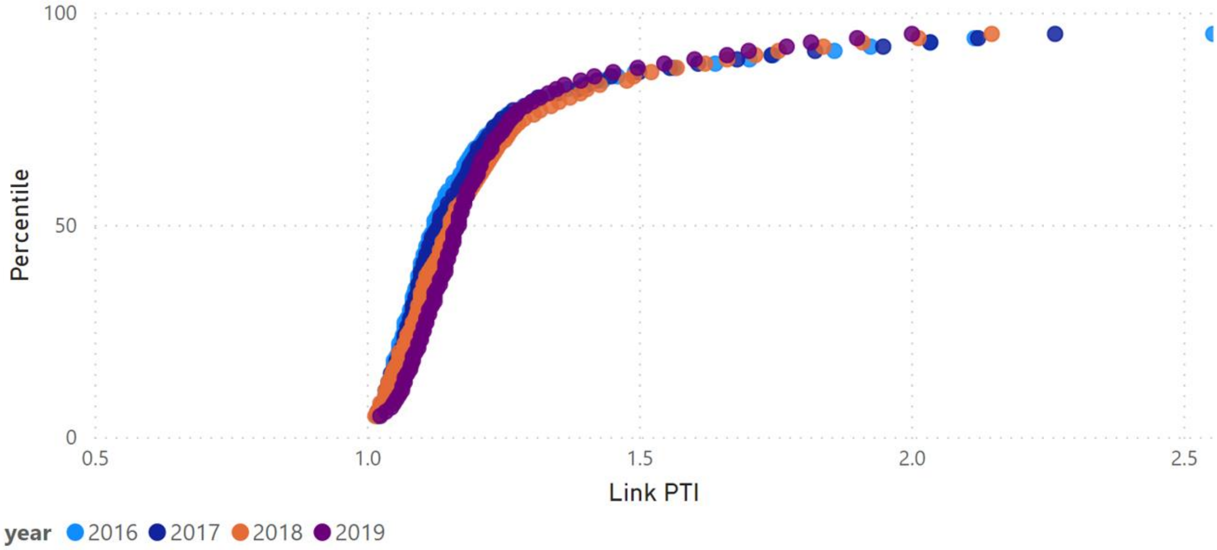



**(b)**

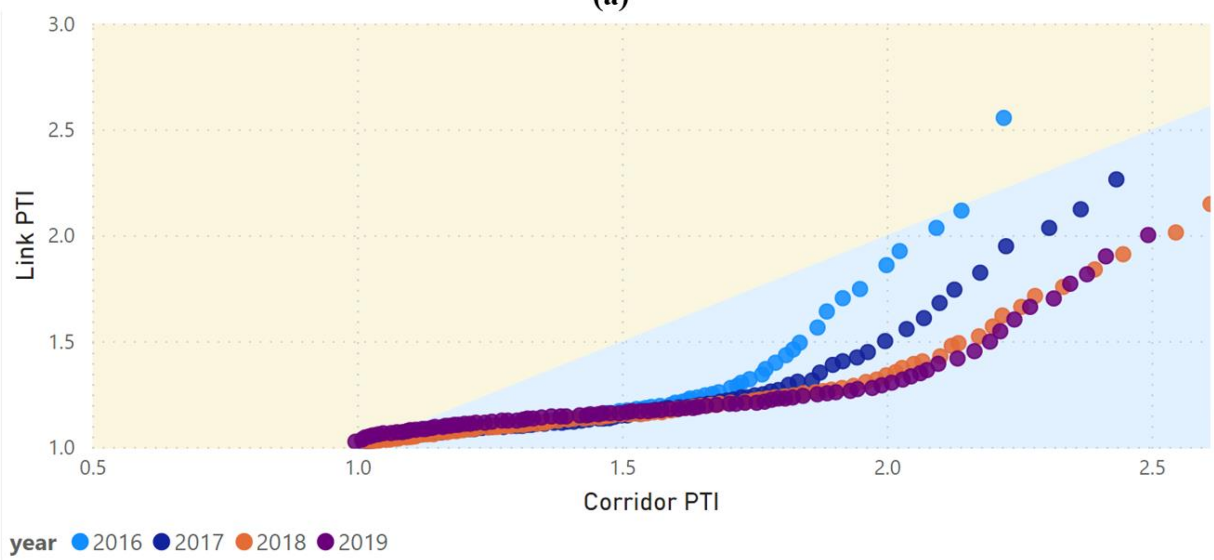



**(c)**

**Figure 23. Examples Using I-66 Eastbound: (a) link planning time index (PTI) cumulative distribution function; (b) corridor PTI cumulative distribution function; (c) corridor vs. link PTI by percentile. Each color represents a link, and each shape represents a corridor.**




**(a)**




**(b)**

**Figure 24. Year-to-Year Comparison of Planning Time Index (PTI) Cumulative Distribution Functions for I-95N Dumfries to Capital Beltway: (a) a link (I-95N Exit 167 to Exit 169); (b) the link-corridor pair.**

## Exploration of Spatiotemporal Context With Systemic Reliability Measures to Identify Unreliable Links

When the systemic reliability measures are used, timestamps become available for integration into the combined link-corridor reliability analysis. For two links within the I-95 Northbound Dumfries to Capital Beltway corridor (which contains a total of seven links), Figure 25 compares the link vs. corridor systemic PTI values at each timestamp (i.e., every hour) in the analysis period. The 2019 AM peak period contains 1,044 hours for each link-corridor pair. In this figure, each vertical slice represents a specific timestamp for a corridor.

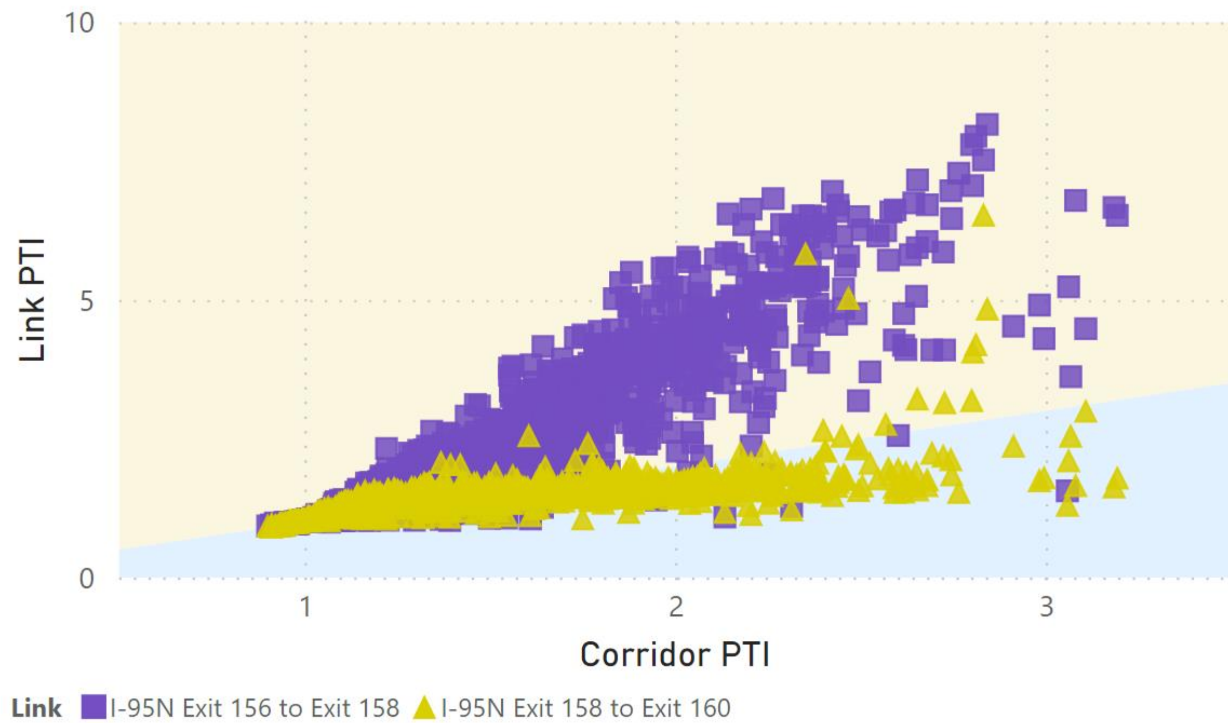
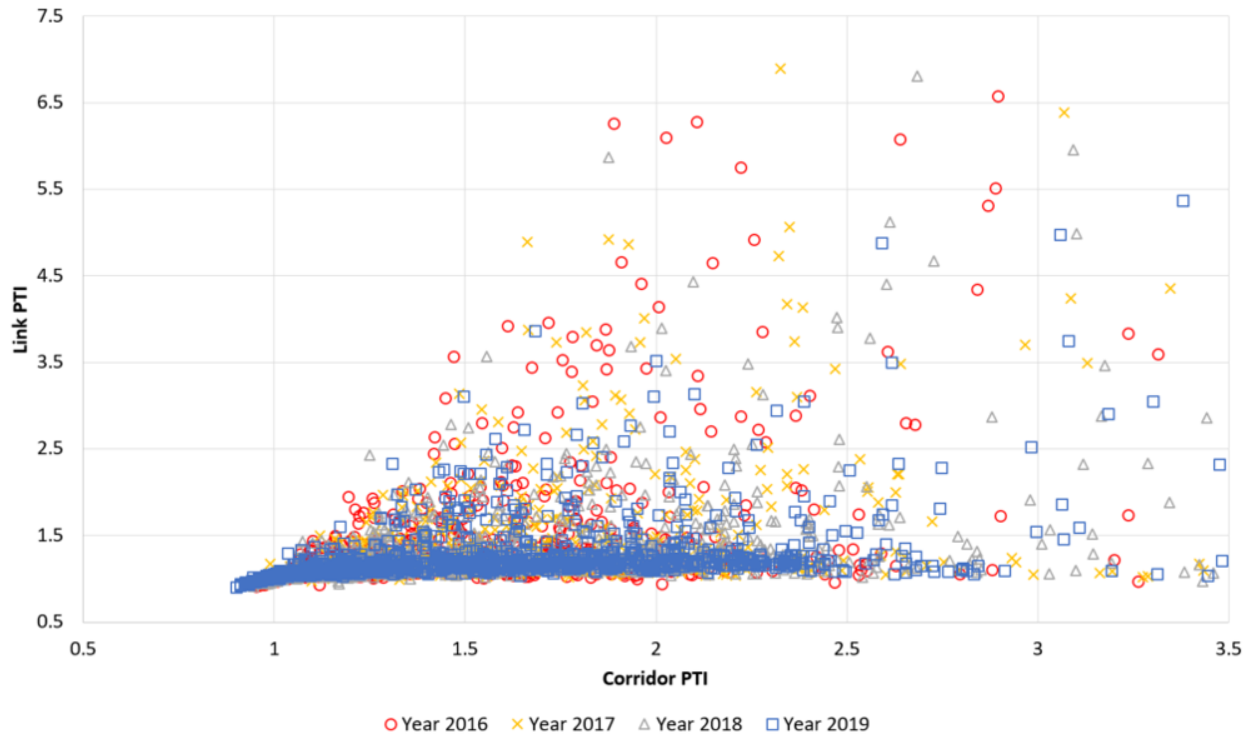


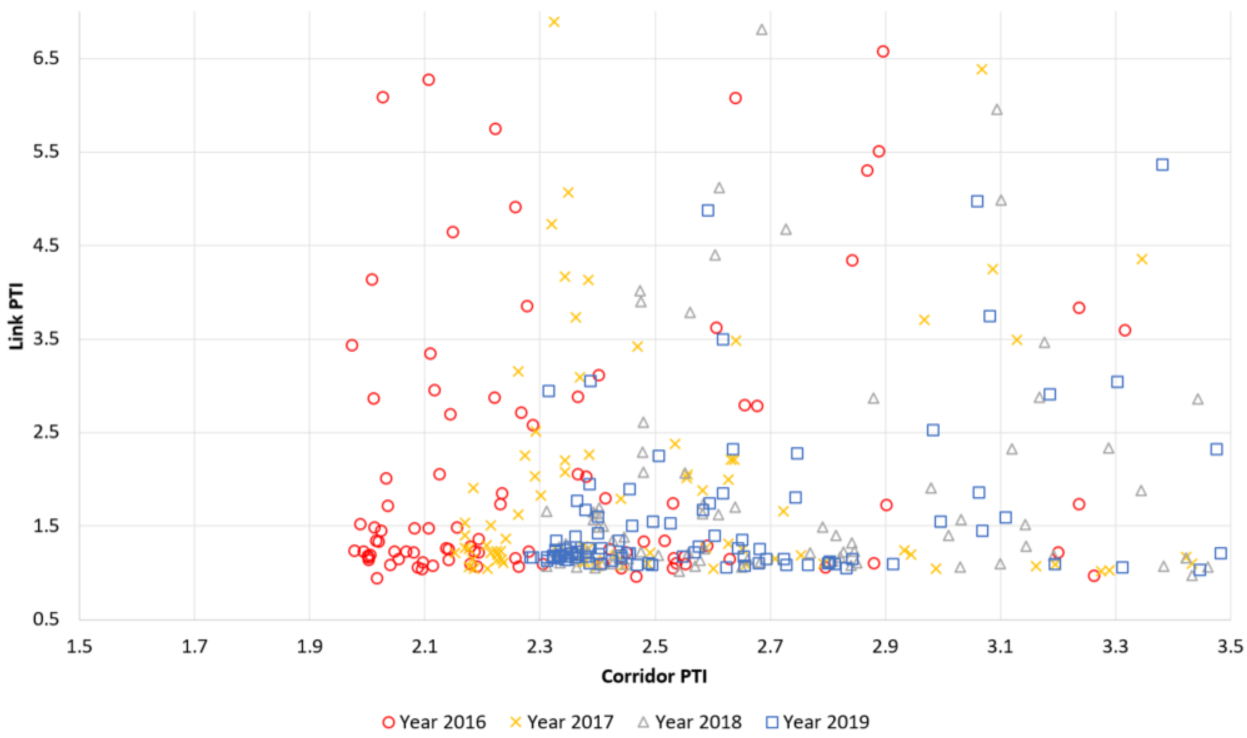

**Figure 25. Example of Corridor vs. Link Planning Time Index (PTI) by Timestamp Using the I-95N Dumfries to Capital Beltway Corridor During the 2019 AM Peak Period**

Although there is a strong positive correlation between the PTI values by timestamp for the most unreliable links and their parent corridor, the link PTI values do not necessarily increase homogeneously with their corridor PTI values; i.e., all four reliable-unreliable possibilities are observed in the field for link-corridor pairs depending on traffic demand fluctuations and actual locations of capacity-restricting events. Whereas an incident just downstream from a link may make a link have high travel time, a lane-blocking incident just upstream of a link in the peak period is likely to create free-flow conditions at that link. If the traffic demand is not high enough and only one of a total two lanes is closed because of an event, the link is not likely to have any congestion, irrespective of the event location.

Figure 26(a) is the equivalent of Figure 24 in comparing year-to-year changes in the link-corridor pair PTI values using timestamps. The link PTI values in Figure 26(a) are relatively stable before the corridor PTI value reaches 1.5, similar to the observations in Figure 24(b). Figure 26(b) shows a portion of Figure 26(a), focusing on the top 20 percentile values of the corridor PTI from each year. Although the link PTI values show high variability when the corridor is unreliable, the correlations between link and corridor PTIs are not as noticeable as in Figure 24. However, when the vertical slices in Figure 26(b) are looked at left to right, 2016 values dominate the leftmost panel, followed by 2017, and then 2019 (which closely mirrors 2018).



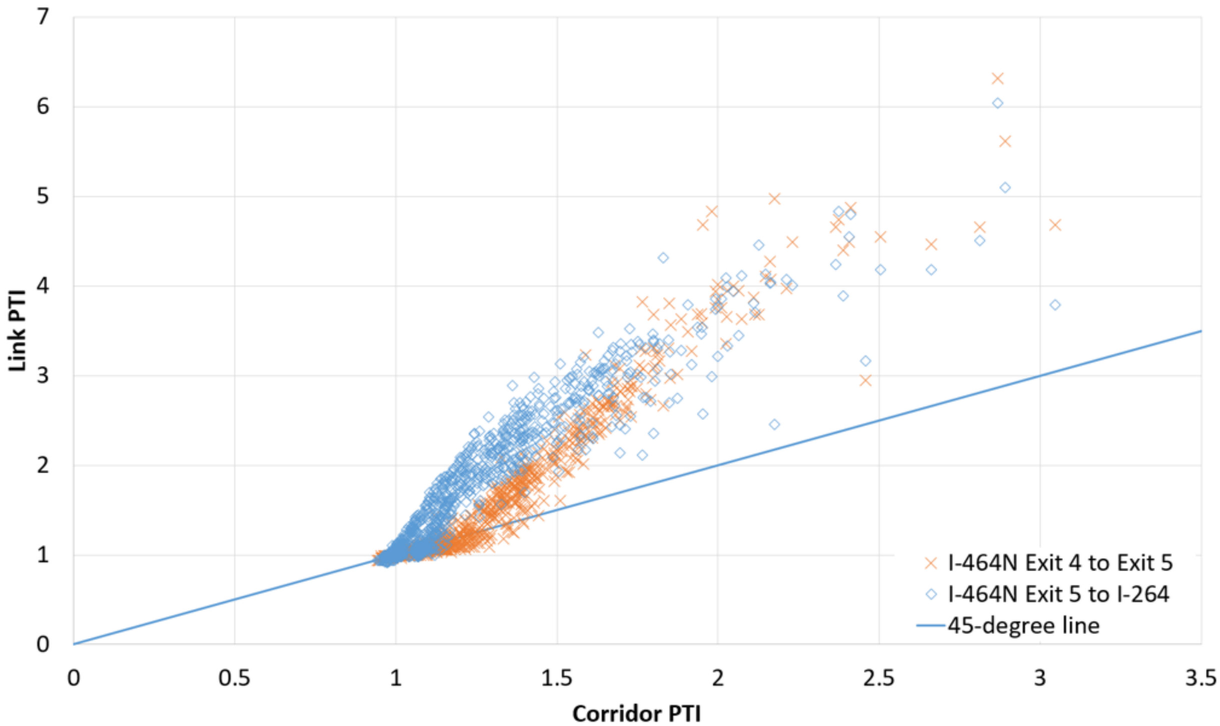
(a)



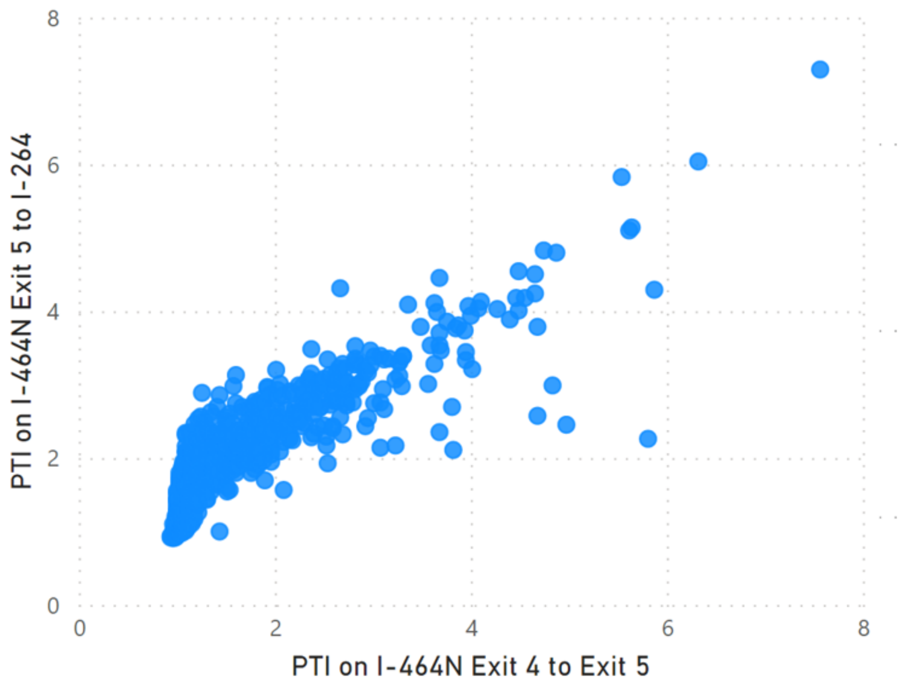
(b)

**Figure 26. Year-to-Year Comparison of Systemic Planning Time Index (PTI) Values for the Link I-95N Exit 167 to Exit 169 Within the I-95N Dumfries to Capital Beltway Corridor: (a) all timestamps; (b) top 100 corridor travel time timestamps. A few very high percentile data points are not shown for the sake of clarity.**

With the spatiotemporal correlations available from the systemic PTI values, different links within a corridor with unreliable travel times concurrently can be examined together (see Figure 27).




(a)




(b)

**Figure 27. Comparison of Planning Time Index (PTI) Between (a) Two Concurrently Unreliable Links Along With Their Parent Corridor, and (b) the Same Two Concurrently Unreliable Links Directly**

Figure 27(a) shows two such links within a corridor, juxtaposed with the corridor PTI values. Figure 27(b) shows the PTI values of the same two links paired by timestamp. Even when two such links are separated by other links in between them, one can logically infer that improving the reliability at just one of these two concurrently unreliable links will not improve the corridor reliability. In contrast, a single unreliable link within a highly reliable corridor points to hotspot unreliable locations such as interchanges with other major corridors. Improving that one link will improve the travel time reliability for the entering/exiting traffic.

## Design and Application of the Systemic Screening Methodology

Table 2 shows the results of the Top 20-20 network screening for the I-95 Northbound Dumfries to I-495 Capital Beltway corridor in the 2019 AM peak period. Of the total 1,044 AM peak hours in 2019, the top 20 percentile corresponds to 209 hours (=1,044 x 20%) individually for every link and every corridor. The number of hours in the Top 20-20 percentiles for each link representing the number of timestamps that both the link and the corridor are unreliable will be less than or equal to 209 hours. In Table 2, the link I-95N Exit 156 to Exit 158 has a value of 160 hours; i.e., the corridor is concurrently unreliable with this link during those 160 hours, and this link had greater unreliability (with higher PTI values) than the corridor. Since the Top 20-20 method considers all the timestamps in the top 20th percentile of both the links and the corridors, the link or corridor PTI available from this filtered dataset may not relate to any specific percentile of interest. Depending on the distribution of the travel time data, any percentile at or above the 80th percentile might be part of this filtered dataset.

To provide some basis for the analyst to compare these new systemic results with the traditional results, the minimum link PTI and the minimum corridor PTI of this final results dataset are also provided in Table 2. Having timestamps in the screening process also enables the identification of two closely spaced unreliable links in Table 2, i.e., I-95N Exit 156 to Exit 158 and I-95N Exit 161 to Exit 163, to be highly related in time. The first link has 160 hours of its top 20 percentile unreliable hours overlapping with the top 20 percentile unreliable corridor hours. The second link has 111 hours that overlap between these corresponding values. A total of 67 hours were common between these two values.

**Table 2. Example Result of the Top 20-20 Network Screening Method From the 2019 AM Peak Period for the I-95 Northbound Dumfries to I-495 Capital Beltway Corridor**

| Link | No. of Hours in Top 20-20 | Min. Link PTI | Min. Corridor PTI |
|---|---|---|---|
| I-95N Exit 152 to Exit 156 | 11 | 2.43 | 2.16 |
| I-95N Exit 156 to Exit 158 | 160 | 4.12 | 2.03 |
| I-95N Exit 158 to Exit 160 | 17 | 2.23 | 2.18 |
| I-95N Exit 160 to Exit 161 | 70 | 2.09 | 2.03 |
| I-95N Exit 161 to Exit 163 | 111 | 2.27 | 2.03 |
| I-95N Exit 163 to Exit 166 | 52 | 2.13 | 2.03 |
| I-95N Exit 166 to Exit 167 | 32 | 2.09 | 2.03 |
| I-95N Exit 167 to Exit 169 | 15 | 2.13 | 2.03 |

PTI = planning time index.

Simply solving the upstream unreliability problem may worsen the downstream link unreliability, as they are highly spatiotemporally related, unless the upstream link is a completely independent hotspot due to ramp traffic. This spatiotemporal relation articulates the need for more analyses of traffic volumes, geometry, etc., and for a careful design of the corridor reliability improvement plans. Table 2 provides a starting point for identifying these additional analysis needs.

Table 3 presents the top 15 unreliable links in the entire study area identified by the Top 20-20 method, the traditional PTI-80 measure, and the traditional PTI-95 measure.

**Table 3. The Top 15 Unreliable Links Identified by the Top 20-20 Method, PTI-95, and PTI-80**

| Rank | Link by Top 20-20 | Top 20-20 Hours | Link by PTI-95 | PTI-95 | Link by PTI-80 | PTI-80 |
|---|---|---|---|---|---|---|
| 1 | I-464N Exit 4 to Exit 5 | 195 | I-395N Exit 8 to Exit 10 | 8.78 | I-395N Exit 8 to Exit 10 | 6.30 |
| 2 | I-95N Exit 169 to Exit 170 | 193 | I-64E Exit 267 to Exit 268 | 6.31 | I-64E Exit 267 to Exit 268 | 5.00 |
| 3 | I-95N Exit 170 to Exit 173 | 190 | I-64E Exit 265 to Exit 267 | 6.29 | I-95N Exit 156 to Exit 158 | 4.11 |
| 4 | Powhite Pkwy (VA76) NB–Jahnke Rd | 190 | I-95N Exit 156 to Exit 158 | 5.85 | I-395N Exit 3 to Exit 4 | 3.71 |
| 5 | George Washington Memorial Pkwy SB–Spout Run Pkwy | 187 | I-66E Exit 44 to Exit 47 | 5.42 | I-64E Exit 265 to Exit 267 | 3.56 |
| 6 | Harry Byrd Hwy (VA7) EB–VA-704 | 184 | I-395N Exit 3 to Exit 4 | 4.85 | I-64W Exit 296 to Exit 297 | 3.44 |
| 7 | Harry Byrd Hwy (VA7) EB–VA-9 (Paeonian Springs)(West) | 184 | I-95N Exit 169 to Exit 170 | 4.80 | I-66E Exit 44 to Exit 47 | 3.37 |
| 8 | I-64W I-95 to Exit 192 | 184 | I-395N Exit 2 to Exit 3 | 4.77 | I-66E Exit 55 to Exit 57 | 3.30 |
| 9 | I-64E Exit 265 to Exit 267 | 183 | I-64W Exit 296 to Exit 297 | 4.70 | I-395N Exit 2 to Exit 3 | 3.25 |
| 10 | WWII Veterans Mem Hwy (VA288) NB–Huguenot Trail | 183 | I-66E Exit 55 to Exit 57 | 4.39 | I-395N Exit 10 to Stateline | 3.15 |
| 11 | Powhite Pkwy (VA76) NB–VA-150-Chippenham Pkwy | 182 | George Washington Memorial Pkwy SB-Spout Run Pkwy | 4.23 | I-66E Exit 75 to Stateline | 3.00 |
| 12 | I-66W Exit 69 to Exit 71 | 181 | I-395N Exit 10 to Stateline | 3.81 | I-395N Exit 4 to Exit 5 | 2.88 |
| 13 | I-264E Exit 6 to Exit 7 | 179 | I-395N Exit 4 to Exit 5 | 3.75 | I-495N Exit 43 to Exit 44 | 2.78 |
| 14 | I-464N Exit 5 to I-264 | 179 | I-395N Exit 7 to Exit 8 | 3.72 | Harry Byrd Hwy (VA7) EB–VA-9 (Paeonian Springs)(West) | 2.66 |
| 15 | Dulles Toll Road (VA 267) EB-Va-28-Exit 9B | 174 | I-264E Exit 6 to Exit 7 | 3.72 | George Washington Memorial Pkwy SB-Spout Run Pkwy | 2.61 |

Tables 4, 5, and 6 show the top 15 links identified by the Top 20-20 method, the PTI-95 measure, and the PTI-80 measure, respectively, and their corresponding ranks by the two other traditional methods. First, it is noted that the list of top 15 links generated from the PTI-80 and the PTI-95 measures do not closely align. This is a significant concern with point-based estimates. Only a handful of links overlap across two or all the three top 15 links list. Whereas the PTI-80 and PTI-95 link lists heavily center on the interstates, the Top 20-20 method identified a number of links on other LAFs as well. In addition to the inherent differences among these different methods/measures, the selected link PTI threshold value, the corridor PTI threshold value, and the percentile thresholds of 20 and 20 could have played some role in the actual links selected by the Top 20-20 method. However, small changes to these values (link PTI threshold of 1.3, 1.4, 1.6, 1.7; corridor PTI threshold of 1.1, 1.2, 1.3; link/corridor percentile thresholds of 30, 25, 15) were tested for sensitivity, and they did not affect the results noticeably.

The topmost link identified by the Top 20-20 method, I-464N Exit 4 to Exit 5, is about 1.5 miles upstream of a drawbridge that is regularly opened for maritime traffic. Although the PTI-80 and PTI-95 measures indicate relatively high unreliability for this link, they do not place this link in their top 15 unreliable lists. What is notable is the new quantified identification of how much this link's unreliability is correlated with the corridor unreliability, i.e., how much this link directly affects (or is affected by) the corridor unreliability. This provides decision makers with new knowledge that they can use in conjunction with the traditional analysis results. It is also noted that the top 200 unreliable links identified by the Top 20-20 method showed an overlap of 174 links, or 87%, with the PTI-95 measure (R-square of 0.59) and an overlap of 137 links, or 69% ,with the PTI-80 measure (R-square of 0.23) (see Figure 28). Between the PTI-80 and PTI-95 measures, the overlap was 195 links, or 98% (R-square of 0.70). However, the ranks of individual links can be different.

**Table 4. The Top 15 Unreliable Links Identified by PTI-95 and Their Ranks by the Other Methods**

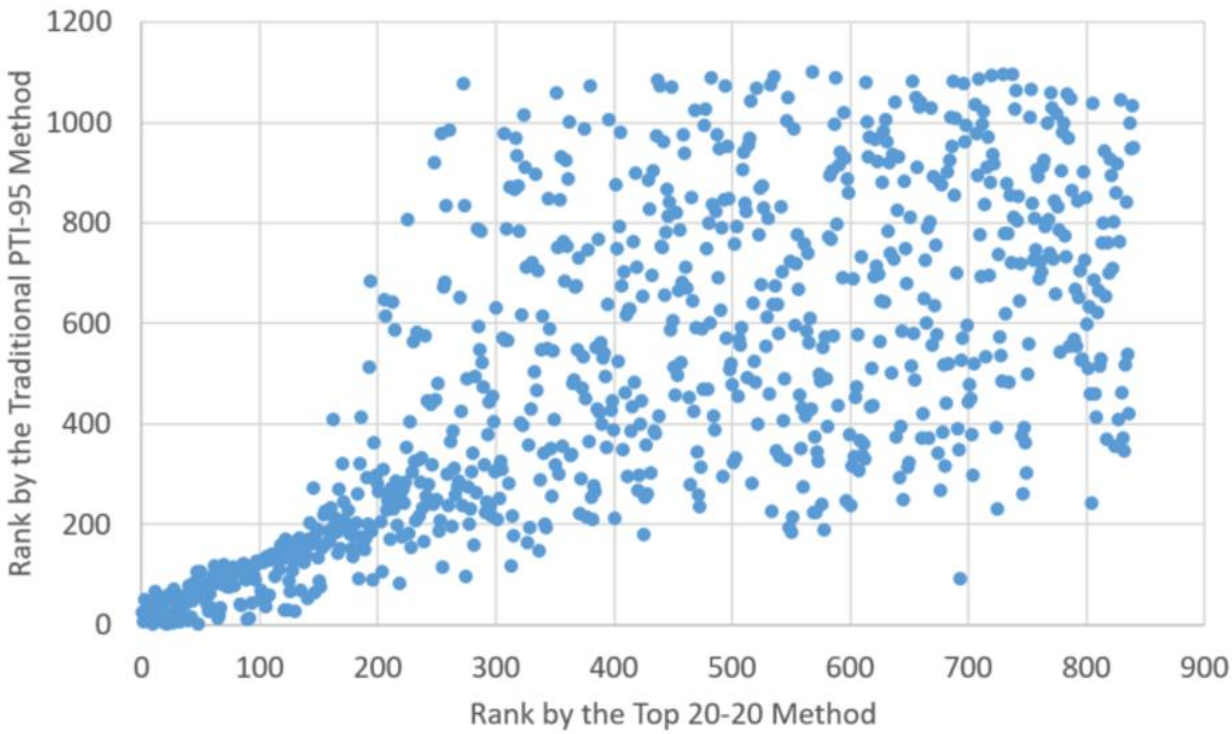
| Link by PTI-95 | Rank by PTI-95 | PTI-95 | Rank by PTI-80 | PTI-80 | Rank by Top 20-20 | No. of Hours in Top 20-20 |
|---|---|---|---|---|---|---|
| I-395N Exit 8 to Exit 10 | 1 | 8.78 | 1 | 6.30 | 48 | 121 |
| I-64E Exit 267 to Exit 268 | 2 | 6.31 | 2 | 5.00 | 21 | 168 |
| I-64E Exit 265 to Exit 267 | 3 | 6.29 | 5 | 3.56 | 9 | 183 |
| I-95N Exit 156 to Exit 158 | 4 | 5.85 | 3 | 4.11 | 26 | 160 |
| I-66E Exit 44 to Exit 47 | 5 | 5.42 | 7 | 3.37 | 19 | 170 |
| I-395N Exit 3 to Exit 4 | 6 | 4.85 | 4 | 3.71 | 32 | 145 |
| I-95N Exit 169 to Exit 170 | 7 | 4.80 | 35 | 2.02 | 2 | 193 |
| I-395N Exit 2 to Exit 3 | 8 | 4.77 | 9 | 3.25 | 39 | 136 |
| I-64W Exit 296 to Exit 297 | 9 | 4.70 | 6 | 3.44 | 24 | 162 |
| I-66E Exit 55 to Exit 57 | 10 | 4.39 | 8 | 3.30 | 16 | 174 |
| George Washington Memorial Pkwy SB-Spout Run Pkwy | 11 | 4.23 | 15 | 2.61 | 5 | 187 |
| I-395N Exit 10 to Stateline | 12 | 3.81 | 10 | 3.15 | 89 | 72 |
| I-395N Exit 4 to Exit 5 | 13 | 3.75 | 12 | 2.88 | 65 | 107 |
| I-395N Exit 7 to Exit 8 | 14 | 3.72 | 23 | 2.28 | 91 | 70 |
| I-264E Exit 6 to Exit 7 | 15 | 3.72 | 20 | 2.34 | 13 | 179 |

**Table 5. The Top 15 Unreliable Links Identified by PTI-80 and Their Ranks by the Other Methods**

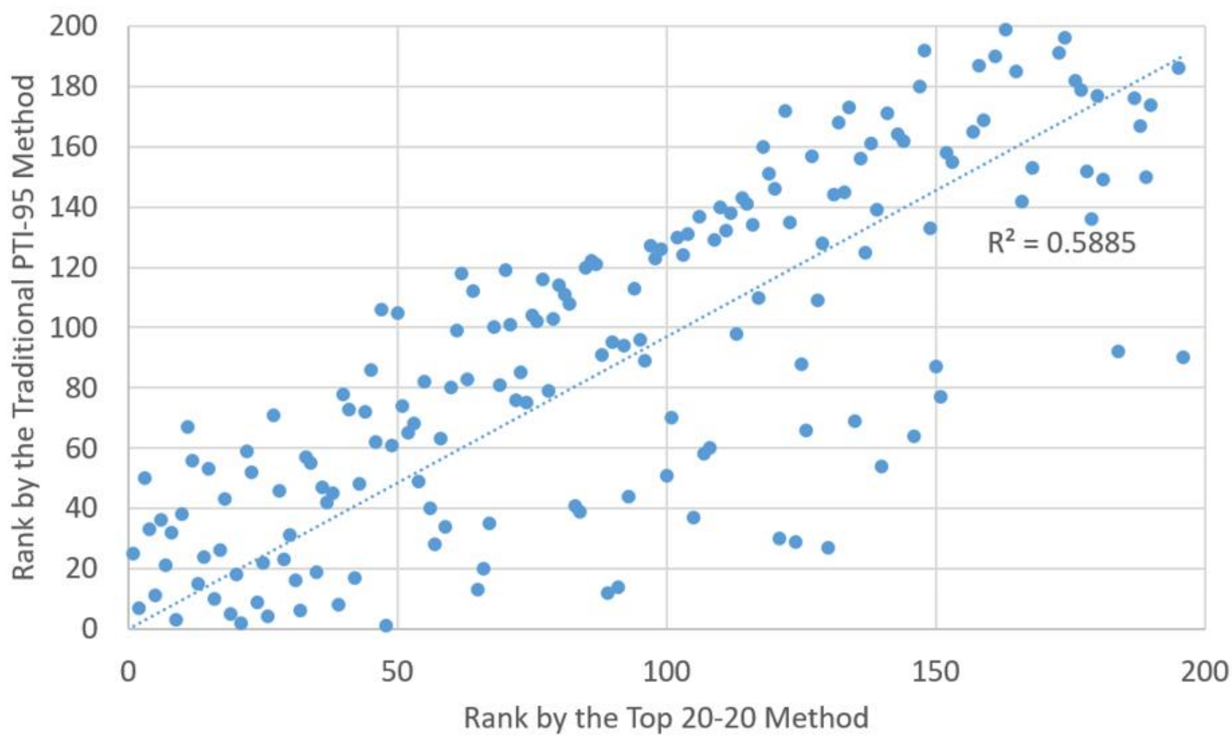
| Link by PTI-80 | Rank by PTI-80 | PTI-80 | Rank by PTI-95 | PTI-95 | Rank by Top 20-20 | No. of Hours in Top 20-20 |
|---|---|---|---|---|---|---|
| I-395N Exit 8 to Exit 10 | 1 | 6.30 | 1 | 8.78 | 48 | 121 |
| I-64E Exit 267 to Exit 268 | 2 | 5.00 | 2 | 6.31 | 21 | 168 |
| I-95N Exit 156 to Exit 158 | 3 | 4.11 | 4 | 5.85 | 26 | 160 |
| I-395N Exit 3 to Exit 4 | 4 | 3.71 | 6 | 4.85 | 32 | 145 |
| I-64E Exit 265 to Exit 267 | 5 | 3.56 | 3 | 6.29 | 9 | 183 |
| I-64W Exit 296 to Exit 297 | 6 | 3.44 | 9 | 4.70 | 24 | 162 |
| I-66E Exit 44 to Exit 47 | 7 | 3.37 | 5 | 5.42 | 19 | 170 |
| I-66E Exit 55 to Exit 57 | 8 | 3.30 | 10 | 4.39 | 16 | 174 |
| I-395N Exit 2 to Exit 3 | 9 | 3.25 | 8 | 4.77 | 39 | 136 |
| I-395N Exit 10 to Stateline | 10 | 3.15 | 12 | 3.81 | 89 | 72 |
| I-66E Exit 75 to Stateline | 11 | 3.00 | 26 | 3.25 | 17 | 171 |
| I-395N Exit 4 to Exit 5 | 12 | 2.88 | 13 | 3.75 | 65 | 107 |
| I-495N Exit 43 to Exit 44 | 13 | 2.78 | 17 | 3.65 | 42 | 132 |
| Harry Byrd Hwy (VA7) EB–VA-9 (Paeonian Springs)(West) | 14 | 2.66 | 21 | 3.46 | 7 | 184 |
| George Washington Memorial Pkwy SB-Spout Run Pkwy | 15 | 2.61 | 11 | 4.23 | 5 | 187 |

**Table 6. The Top 15 Unreliable Links Identified by the Top 20-20 Method and Their Ranks by the Other Methods**

| Link by Top 20-20 | Rank by Top 20-20 | No. of Hours in Top 20-20 | Rank by PTI-80 | PTI-80 | Rank by PTI-95 | PTI-95 |
|---|---|---|---|---|---|---|
| I-464N Exit 4 to Exit 5 | 1 | 195 | 45 | 1.83 | 26 | 3.26 |
| I-95N Exit 169 to Exit 170 | 2 | 193 | 35 | 2.02 | 7 | 4.80 |
| I-95N Exit 170 to Exit 173 | 3 | 190 | 38 | 1.97 | 51 | 2.73 |
| Powhite Pkwy (VA76) NB – Jahnke Rd | 4 | 190 | 33 | 2.05 | 34 | 3.00 |
| George Washington Memorial Pkwy SB–Spout Run Pkwy | 5 | 187 | 15 | 2.61 | 11 | 4.23 |
| Harry Byrd Hwy (VA7) EB–VA-704 | 6 | 184 | 66 | 1.54 | 37 | 2.94 |
| Harry Byrd Hwy (VA7) EB–VA-9 (Paeonian Springs)(West) | 7 | 184 | 14 | 2.66 | 22 | 3.46 |
| I-64W I-95 to Exit 192 | 8 | 184 | 32 | 2.08 | 33 | 3.04 |
| I-64E Exit 265 to Exit 267 | 9 | 183 | 5 | 3.56 | 3 | 6.29 |
| WWII Veterans Mem Hwy (VA288) NB–Huguenot Trail | 10 | 183 | 36 | 1.99 | 39 | 2.89 |
| Powhite Pkwy (VA76) NB – VA-150-Chippenham Pkwy | 11 | 182 | 46 | 1.80 | 68 | 2.29 |
| I-66W Exit 69 to Exit 71 | 12 | 181 | 27 | 2.16 | 57 | 2.51 |
| I-264E Exit 6 to Exit 7 | 13 | 179 | 20 | 2.34 | 16 | 3.72 |
| I-464N Exit 5 to I-264 | 14 | 179 | 19 | 2.36 | 25 | 3.30 |
| Dulles Toll Road (VA 267) EB-Va-28-Exit 9B | 15 | 174 | 73 | 1.41 | 54 | 2.59 |




**(a)**




**(b)**

**Figure 28. Comparison of Limited Access Facility Link Unreliability Ranks by the Systemic Top 20-20 and PTI-95 Methods: (a) all links in the study network; (b) top 200 links by both methods.**

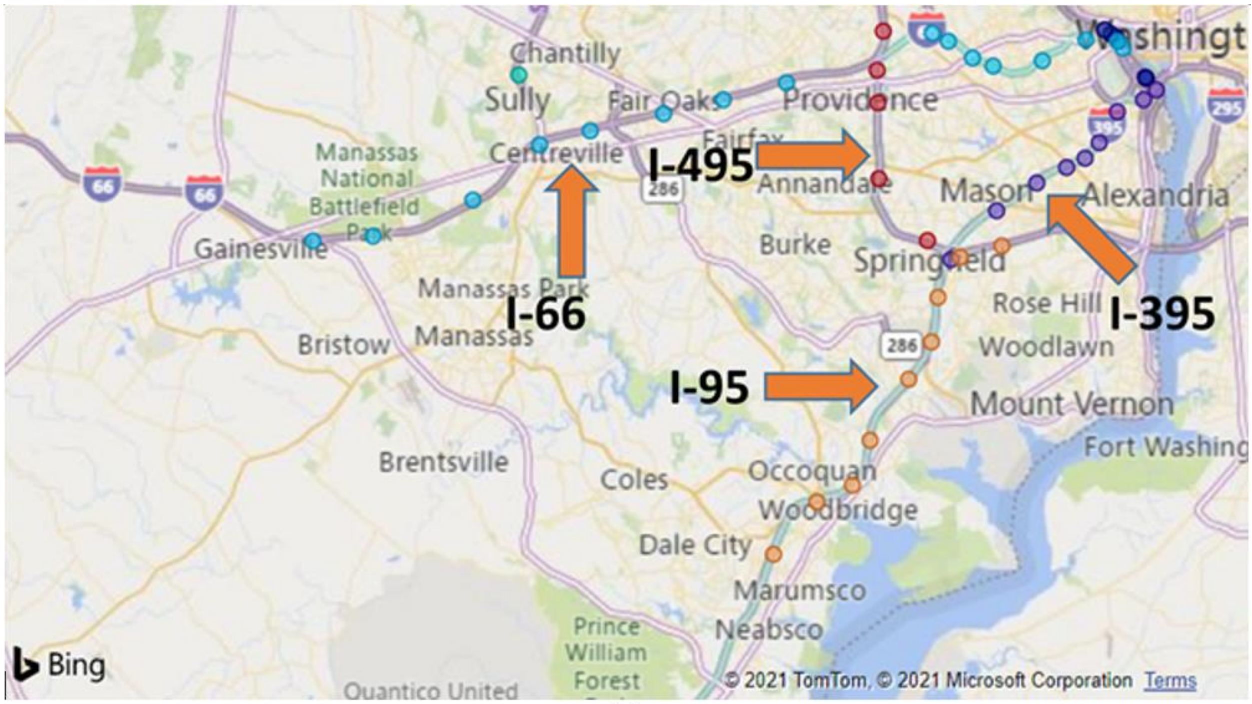
Figure 29 compares the top 100 unreliable links identified by the traditional PTI-80 vs. the Top 20-20 methods near Washington, D.C. I-66, I-95, I-395, and I-495 are some of the most unreliable highways in Virginia, serving as main regional commuting routes. Whereas the traditional method has a tendency to mark almost all the links on these routes as unreliable, the Top 20-20 method identified the most unreliable links within each unreliable corridor on each route with the highest correlation to the corridor unreliability. Across the study network, in the top 200 unreliable links by each method, the Top 20-20, PTI-95, and PTI-80 methods identified 95, 66, and 65 unique corridors, respectively. Of those corridors identified by the traditional methods, only 3 of 65 unique corridors identified by the PTI-80 method and 4 of 66 by the PTI-95 method were not identified by the Top 20-20 method. Those link-corridors are either a single-link corridor or an unreliable hotspot. Figure 30 shows an example of a link and its corridor systemic PTI values paired by timestamp for an unreliable hotspot. Whereas the link PTI value was more than 6 in this case, the corridor PTI stayed under 1.4, and the link was unreliable mostly when the corridor was reliable.

## Combined Causal Analysis of Links and Corridors

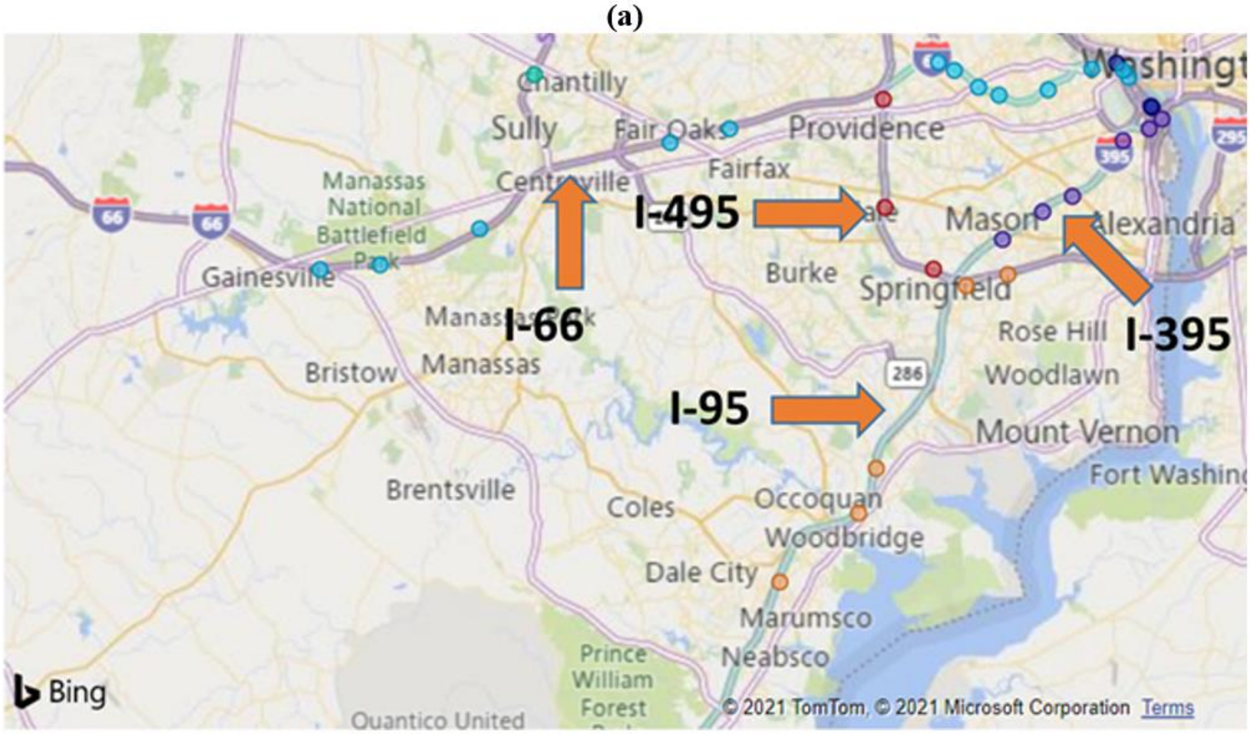
The availability of timestamps in the new network screening process also provides a new opportunity to perform combined causal analysis of links and corridors and paves the way to potential solutions for corridor unreliability problems. Tables 7 and 8 show examples of combined causal analysis results for a rural and an urban corridor, respectively, for incidents, work zones, and weather events. These tables show the number of timestamps associated with different independent causes, under different scenarios, on different links, and with their parent corridor. These scenarios and sub-figures include (a) all AM peak hours; (b) top 20 percentile unreliable hours of each link separately; (c) top 20 percentile unreliable hours of the corridor separately; and (d) hours identified by the Top 20-20 method.

Each row in each sub-table in Table 7 shows the number of hours for a link/corridor under consideration. For example, the first row in Table 7(a) shows details for the link I-81N Exit 105 to Exit 109. There are a total of 1,044 hours in the 2019 AM peak period; for 39 of those 1,044 hours, there was at least one incident associated with the corridor, and for 6 of those 1,044 hours, there was an incident associated with the link. Since multiple links within a corridor can be associated with incidents during the same hour, the sum of incident hours by links does not equal the incident hours for the corridor. Following are two examples showing different ways of interpreting the combined link-corridor causal analysis results.

Table 7 shows the results of the causal analysis for the rural I-81N Roanoke City corridor, which is a relatively mountainous, high heavy-vehicle usage route. From an individual link perspective, link I-81N Exit 118 to Exit 128 is associated with incidents for a total of 13 hours (see Table 7[a]). When Tables 7(a) and 7(b) are compared, all of these 13 hours (100%) are in the top 20 percentile of the link travel times.




**(a)**




**(b)**

**Figure 29. Comparison of Results in Washington, D.C., Area From the Top 100 Unreliable Links in the Study Area as Identified by (a) the Traditional Planning Time Index-80 Method, and (b) the Top 20-20 Method. Each link is represented by its midpoint, and each route by a color.**

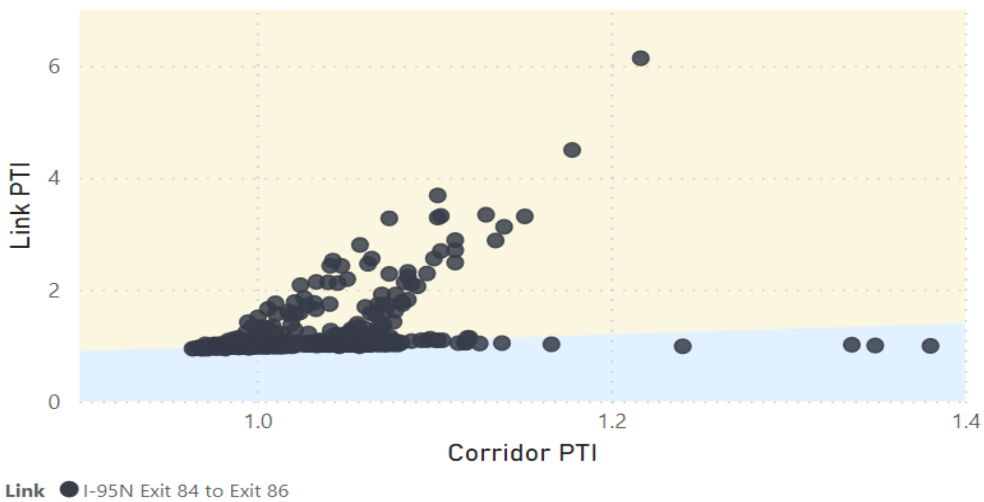



**Figure 30. Example of Corridor vs. Link Planning Time Index (PTI) by Timestamp at an Unreliable Hotspot, I-95N Exit 84 to Exit 86, During the 2019 AM Peak Period**

For the I-81N Roanoke City corridor as a whole, a total of 39 hours are associated with incidents. When Tables 7(a) and (c) are compared, 34 of these 39 hours (87%) are in the top 20 percentile of the corridor travel times. Based on these analyses, incidents seem to be one of the primary causes of travel time unreliability in this corridor. Moreover, as shown in Table 7(d), the number of hours affected by incidents on all links is highly related to the number of hours in the Top 20-20 link-corridor unreliable hours. This observation strengthens the hypothesis that incidents on various links in this corridor likely have significant impacts on the unreliability of both the link and the corridor.

In contrast, a total of 110 hours are associated with work zone events on this corridor. However only 9 of those 110 hours (8%) made it to the top 20 percentile of the corridor travel times, and only 1 to 2 hours in the Top 20-20 link-corridor unreliable hours are associated with work zone events. This observation could suggest that work zone events had a relatively negligible impact on the corridor unreliability.

Table 8 shows the results of the causal analysis for the urban I-395N Arlington County corridor, which is a relatively high-traffic-volume commuting route between Virginia and Washington, D.C. From an individual link perspective, nearly all links within the corridor are associated with weather events and work zones to some degree (see Table 8[a]); however, none of those hours are in the top 20 percentile of the link travel times (see Table 8[b]). In a comparison of Tables 8(a) and 8(d), only a handful of event-hours associated with the links made it to the Top 20-20 link-corridor unreliable hours, suggesting that there is no clear correlation between known causes and link-corridor unreliability. Two possible reasons for this are that (1) the causal events occurred predominantly beyond the state line, and (2) the traffic demand variation is one of the major causes of unreliability. The last link within the corridor, link I-395N Exit 10 to State Line, connects to Washington, D.C., and the events that occurred beyond the state line were not included in the datasets analyzed in this study. With the facility operating near its capacity in the AM peak period, any traffic demand fluctuations can drive the facility into unstable states and longer travel times.

**Table 7. A Rural Example of the Link-Corridor Causal Analysis Results for the I-81N Roanoke City Corridor Showing (a) All Hours in the AM Peak Period in 2019, (b) Top 20 Percentile Unreliable Hours of Each Link, (c) Top 20 Percentile Unreliable Hours of the Corridor, and (d) Unreliable Link-Corridor Hours Identified by the Top 20-20 Method**

**(a)**

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone – Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-81N Exit 105 to Exit 109 | 1044 | 39 | 6 | 57 | 6 | 110 | 8 | 236 | 116 | 8 | 4 |
| I-81N Exit 109 to Exit 114 | 1044 | 39 | 4 | 57 | 15 | 110 | 17 | 236 | 131 | 8 | 8 |
| I-81N Exit 114 to Exit 118 | 1044 | 39 | 0 | 57 | 14 | 110 | 56 | 236 | 91 | 8 | 8 |
| I-81N Exit 118 to Exit 128 | 1044 | 39 | 13 | 57 | 9 | 110 | 31 | 236 | 50 | 8 | 8 |
| I-81N Exit 128 to Exit 132 | 1044 | 39 | 6 | 57 | 8 | 110 | 16 | 236 | 70 | 8 | 8 |
| I-81N Exit 132 to Exit 137 | 1044 | 39 | 3 | 57 | 11 | 110 | 6 | 236 | 82 | 8 | 2 |
| I-81N Exit 137 to Exit 140 | 1044 | 39 | 2 | 57 | 19 | 110 | 26 | 236 | 68 | 8 | 2 |
| I-81N Exit 140 to Exit 141 | 1044 | 39 | 0 | 57 | 24 | 110 | 5 | 236 | 100 | 8 | 2 |
| I-81N Exit 141 to Exit 143 | 1044 | 39 | 5 | 57 | 19 | 110 | 3 | 236 | 100 | 8 | 2 |
| I-81N Exit 143 to Exit 146 | 1044 | 39 | 0 | 57 | 15 | 110 | 3 | 236 | 77 | 8 | 2 |

**(b)**

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone – Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-81N Exit 105 to Exit 109 | 209 | 11 | 6 | 9 | 5 | 7 | 1 | 27 | 16 | 4 | 4 |
| I-81N Exit 109 to Exit 114 | 209 | 9 | 4 | 10 | 1 | 8 | 5 | 28 | 12 | 6 | 6 |
| I-81N Exit 114 to Exit 118 | 209 | 15 | 0 | 18 | 10 | 7 | 6 | 17 | 7 | 6 | 6 |
| I-81N Exit 118 to Exit 128 | 209 | 23 | 13 | 21 | 4 | 7 | 1 | 26 | 3 | 5 | 5 |
| I-81N Exit 128 to Exit 132 | 209 | 12 | 5 | 12 | 3 | 9 | 0 | 22 | 4 | 6 | 6 |
| I-81N Exit 132 to Exit 137 | 209 | 9 | 3 | 11 | 4 | 9 | 0 | 26 | 11 | 5 | 2 |
| I-81N Exit 137 to Exit 140 | 209 | 9 | 0 | 9 | 4 | 7 | 1 | 26 | 12 | 5 | 2 |
| I-81N Exit 140 to Exit 141 | 209 | 13 | 0 | 15 | 8 | 4 | 1 | 32 | 14 | 6 | 2 |
| I-81N Exit 141 to Exit 143 | 209 | 9 | 3 | 14 | 7 | 1 | 1 | 35 | 15 | 4 | 2 |
| I-81N Exit 143 to Exit 146 | 209 | 3 | 0 | 11 | 6 | 7 | 1 | 21 | 4 | 6 | 2 |

**(c)**

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone – Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-81N Exit 105 to Exit 109 | 209 | 34 | 5 | 38 | 5 | 9 | 0 | 29 | 15 | 6 | 4 |
| I-81N Exit 109 to Exit 114 | 209 | 34 | 4 | 38 | 14 | 9 | 5 | 29 | 12 | 6 | 6 |
| I-81N Exit 114 to Exit 118 | 209 | 34 | 0 | 38 | 13 | 9 | 5 | 29 | 12 | 6 | 6 |
| I-81N Exit 118 to Exit 128 | 209 | 34 | 13 | 38 | 6 | 9 | 3 | 29 | 5 | 6 | 6 |
| I-81N Exit 128 to Exit 132 | 209 | 34 | 6 | 38 | 4 | 9 | 1 | 29 | 8 | 6 | 6 |
| I-81N Exit 132 to Exit 137 | 209 | 34 | 3 | 38 | 6 | 9 | 1 | 29 | 12 | 6 | 2 |
| I-81N Exit 137 to Exit 140 | 209 | 34 | 0 | 38 | 10 | 9 | 2 | 29 | 1 | 6 | 2 |
| I-81N Exit 140 to Exit 141 | 209 | 34 | 0 | 38 | 11 | 9 | 1 | 29 | 14 | 6 | 2 |
| I-81N Exit 141 to Exit 143 | 209 | 34 | 3 | 38 | 8 | 9 | 1 | 29 | 14 | 6 | 2 |
| I-81N Exit 143 to Exit 146 | 209 | 34 | 0 | 38 | 6 | 9 | 1 | 29 | 9 | 6 | 2 |

**(d)**

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone – Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-81N Exit 105 to Exit 109 | 7 | 7 | 4 | 3 | 3 | 1 | 0 | 2 | 1 | 0 | 0 |
| I-81N Exit 109 to Exit 114 | 6 | 4 | 4 | 4 | 0 | 1 | 1 | 2 | 1 | 0 | 0 |
| I-81N Exit 114 to Exit 118 | 8 | 8 | 0 | 8 | 8 | 0 | 0 | 1 | 1 | 0 | 0 |
| I-81N Exit 118 to Exit 128 | 6 | 6 | 6 | 6 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| I-81N Exit 128 to Exit 132 | 6 | 5 | 4 | 6 | 2 | 0 | 0 | 1 | 1 | 0 | 0 |
| I-81N Exit 132 to Exit 137 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-81N Exit 137 to Exit 140 | 2 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-81N Exit 140 to Exit 141 | 2 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-81N Exit 141 to Exit 143 | 2 | 1 | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-81N Exit 143 to Exit 146 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 |

**Table 8. An Urban Example of the Link-Corridor Causal Analysis Results for the I-395N Arlington County Corridor Showing (a) All Hours in the AM Peak Period in 2019, (b) Top 20 Percentile Unreliable Hours of Each Link, (c) Top 20 Percentile Unreliable Hours of the Corridor, and (d) Unreliable Link-Corridor Hours Identified by the Top 20-20 Method**

(a)

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone - Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-395N I-95 to Exit 2 | 1044 | 66 | 8 | 85 | 83 | 34 | 12 | 139 | 135 | 6 | 6 |
| I-395 N Exit 2 to Exit 3 | 1044 | 66 | 10 | 85 | 74 | 34 | 22 | 139 | 121 | 6 | 6 |
| I-395 N Exit 3 to Exit 4 | 1044 | 66 | 2 | 85 | 71 | 34 | 20 | 139 | 119 | 6 | 5 |
| I-395 N Exit 4 to Exit 5 | 1044 | 66 | 9 | 85 | 61 | 34 | 21 | 139 | 117 | 6 | 5 |
| I-395 N Exit 5 to Exit 6 | 1044 | 66 | 5 | 85 | 54 | 34 | 19 | 139 | 113 | 6 | 5 |
| I-395 N Exit 6 to Exit 7 | 1044 | 66 | 5 | 85 | 47 | 34 | 16 | 139 | 106 | 6 | 1 |
| I-395 N Exit 7 to Exit 8 | 1044 | 66 | 10 | 85 | 34 | 34 | 21 | 139 | 94 | 6 | 1 |
| I-395 N Exit 8 to Exit 10 | 1044 | 66 | 19 | 85 | 12 | 34 | 11 | 139 | 58 | 6 | 1 |
| I-395 N Exit 10 to Stateline | 1044 | 66 | 0 | 85 | 0 | 34 | 0 | 139 | 0 | 6 | 0 |

(b)

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone - Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-395N I-95 to Exit 2 | 209 | 26 | 6 | 27 | 25 | 10 | 3 | 17 | 17 | 0 | 0 |
| I-395 N Exit 2 to Exit 3 | 209 | 26 | 2 | 30 | 28 | 2 | 0 | 10 | 10 | 0 | 0 |
| I-395 N Exit 3 to Exit 4 | 209 | 22 | 0 | 27 | 26 | 2 | 0 | 5 | 5 | 0 | 0 |
| I-395 N Exit 4 to Exit 5 | 209 | 21 | 0 | 27 | 24 | 2 | 0 | 4 | 4 | 0 | 0 |
| I-395 N Exit 5 to Exit 6 | 209 | 21 | 1 | 28 | 20 | 4 | 0 | 4 | 4 | 0 | 0 |
| I-395 N Exit 6 to Exit 7 | 209 | 24 | 1 | 29 | 21 | 5 | 2 | 6 | 4 | 0 | 0 |
| I-395 N Exit 7 to Exit 8 | 209 | 15 | 1 | 20 | 14 | 9 | 6 | 10 | 4 | 0 | 0 |
| I-395 N Exit 8 to Exit 10 | 209 | 15 | 8 | 21 | 5 | 14 | 3 | 11 | 0 | 0 | 0 |
| I-395 N Exit 10 to Stateline | 209 | 15 | 0 | 17 | 0 | 15 | 0 | 12 | 0 | 0 | 0 |

(c)

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone - Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-395N I-95 to Exit 2 | 209 | 24 | 3 | 29 | 29 | 2 | 0 | 5 | 5 | 0 | 0 |
| I-395 N Exit 2 to Exit 3 | 209 | 24 | 2 | 29 | 27 | 2 | 0 | 5 | 5 | 0 | 0 |
| I-395 N Exit 3 to Exit 4 | 209 | 24 | 0 | 29 | 27 | 2 | 0 | 5 | 5 | 0 | 0 |
| I-395 N Exit 4 to Exit 5 | 209 | 24 | 3 | 29 | 23 | 2 | 0 | 5 | 5 | 0 | 0 |
| I-395 N Exit 5 to Exit 6 | 209 | 24 | 2 | 29 | 20 | 2 | 0 | 5 | 5 | 0 | 0 |
| I-395 N Exit 6 to Exit 7 | 209 | 24 | 3 | 29 | 16 | 2 | 2 | 5 | 2 | 0 | 0 |
| I-395 N Exit 7 to Exit 8 | 209 | 24 | 3 | 29 | 13 | 2 | 0 | 5 | 1 | 0 | 0 |
| I-395 N Exit 8 to Exit 10 | 209 | 24 | 9 | 29 | 4 | 2 | 0 | 5 | 0 | 0 | 0 |
| I-395 N Exit 10 to Stateline | 209 | 24 | 0 | 29 | 0 | 2 | 0 | 5 | 0 | 0 | 0 |

(d)

| Link | No. of Hours | Incident Hours | | Incident – Impacted Hours | | Work Zone Hours | | Work Zone - Impacted Hours | | Weather Hours | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link | Corridor | Link |
| I-395N I-95 to Exit 2 | 38 | 11 | 2 | 10 | 10 | 1 | 0 | 2 | 2 | 0 | 0 |
| I-395 N Exit 2 to Exit 3 | 136 | 19 | 2 | 22 | 20 | 2 | 0 | 4 | 4 | 0 | 0 |
| I-395 N Exit 3 to Exit 4 | 145 | 18 | 0 | 23 | 22 | 2 | 0 | 4 | 4 | 0 | 0 |
| I-395 N Exit 4 to Exit 5 | 107 | 12 | 0 | 18 | 16 | 2 | 0 | 3 | 3 | 0 | 0 |
| I-395 N Exit 5 to Exit 6 | 39 | 3 | 0 | 5 | 4 | 1 | 0 | 1 | 1 | 0 | 0 |
| I-395 N Exit 6 to Exit 7 | 41 | 5 | 0 | 7 | 5 | 1 | 1 | 1 | 0 | 0 | 0 |
| I-395 N Exit 7 to Exit 8 | 70 | 8 | 0 | 9 | 6 | 0 | 0 | 0 | 0 | 0 | 0 |
| I-395 N Exit 8 to Exit 10 | 121 | 12 | 6 | 16 | 4 | 0 | 0 | 1 | 0 | 0 | 0 |
| I-395 N Exit 10 to Stateline | 72 | 5 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 9 shows for the LAFs the prevalence of all the analyzed causal events concurrent with the Top 20-20 hours compared to all the known events in each period of the day in 2019. Although work zones, weather events, and holidays show a relatively low impact, incidents are associated with 28% to 40% of the Top 20-20 hours. The prevalence of the analyzed causes within the top 20% highest systemic travel times was surprisingly low for some links. Apart from the two reasons mentioned earlier, namely, traffic fluctuations during high travel demand hours and events beyond the state line, limitations regarding causal data event datasets and their interpretation are suspected to be a third reason for this observation. It is noted that all the causal analyses were performed as individual causal events rather than any combination of events.

**Table 9. Prevalence of Concurrent Events in the Top 20-20 Hours in Different Time Periods of the Day in 2019 Across the Study Network Limited Access Facilities**

| Event Hours | Time Period of Day | | | |
|---|---|---|---|---|
| | **AM Peak** | **PM Peak** | **Midday** | **Weekend** |
| Total Incident Hours | 2,605 | 3,570 | 3,635 | 3,249 |
| Top 20-20 Hours With Incidents | 726 (28%) | 1,238 (35%) | 1,365 (38%) | 1,292 (40%) |
| Total Work Zone Hours | 22,139 | 16,985 | 44,625 | 19,224 |
| Top 20-20 Hours With Work Zones | 353 (2%) | 975 (6%) | 2,678 (6%) | 975 (5%) |
| Total Weather Event Hours | 2,509 | 11,560 | 4,838 | 8,631 |
| Top 20-20 Hours With Weather Events | 152 (6%) | 719 (6%) | 409 (8%) | 707 (8%) |
| Total Holiday Hours | 139,057 | 138,754 | 208,147 | 323,744 |
| Top 20-20 Hours With Holidays | 2,693 (2%) | 3,623(3%) | 6,677 (3%) | 18,975 (6%) |

## Validation of Results

Quantitative validation of the methodology presented in this study was not possible as it does not have a direct parallel to other results and traditional methodologies currently available in the literature. Therefore, expert review and feedback were used to validate these methods and results qualitatively. Over six meetings during the project, the data and conflation details, the calculation steps, the results, and the researchers' knowledge and observations were presented to the TRP and the AP, and their critical feedback was discussed in detail and documented.

A summary of these discussions is presented here, grouped as suggestions/feedback, questions, use cases, and research needs. These discussion outcomes were incorporated into the study, recommendations, and/or implementation steps as appropriate.

1. Suggestions/Feedback

    - The TRP and the AP asked the researchers to consider including truck percentage, upstream/downstream impacts, vertical grade, and arterial signal / access density factors for analyzing the systemic performance measures. Of these, truck percentage and upstream/downstream links were obtained, conflated, and added to the analyses. Grade data were available, but it was not clear how to add them meaningfully into this study. Whereas uphill grades are known to slow down some trucks sometimes (rate and length matter), downhill grades often do not affect travel times or reliability. For links and corridors with rolling hills, the appropriate quantitative measure of interest was not clear. Access density data were not readily available on all arterial roads in the study network and developing them was beyond the scope of this study.

- The TRP and the AP selected the PTI and LOTTR measures for detailed study, along with the volume/VMT weights, based on early preliminary results. In that meeting, the TRP, the AP, and the research team decided not to study buffer index, length weight, and AADT weight in detail.

- Several members of the expert panels used the Power BI interactive tool to drill down into the systemic performance measures and factors by themselves to verify the soundness of the results with their expectations. No major concerns were reported from these explorations.

- Given that the MAP-21 weekend hour span from 6 AM to 8 PM often covers several different traffic conditions, the expert panels were interested in analyzing fewer hours during the weekends. They were also interested in more flexibility for an analyst to select hours of interest in the interactive visualization tool. However, given the large file sizes of the results, options for flexible slicing were not feasible in this study.

- Several panel members voiced concerns regarding the need for data storage space, computation memory and CPU needs, and staff skills and time to run the new analyses developed in this study. They also explicitly asked the research team to share the Python code developed in this study and asked the team for additional technology transfer in terms of documentation and guidance, because corridors will change over time and all these resources are needed for the sustainability of this approach going forward.

2. Questions

- Seeing the example of a corridor reliability worsening while the link reliability remained constant, the expert panel wondered if there were any cases with link CDFs improving over the years while the corridor did not improve. After the meeting, the researchers found a few such situations, all of which pertained to very reliable corridors, i.e., the highest PTI was less than 1.2.

- The expert panel appreciated the benefit of the corridor and the systemic approaches but wondered if link-level analyses were still needed. The researchers responded that although the new approaches have new benefits, the traditional approaches are also useful in identifying hotspot unreliable links. Further, the actual definition of the corridor itself plays an important role.

- A question was raised regarding the visualization tool and building a potential web application. Researchers responded that although analyses in the Power BI tool can be customized with queries, developing a web application is deemed a mid-term goal, after the use cases are refined and agreed upon.

3. Use Cases

- When interpreting the systemic section PTI CDF graphs, the expert panel mentioned that sometimes the detour route, not the interstate, is the main problem to be fixed and that this analysis may help them find such situations.

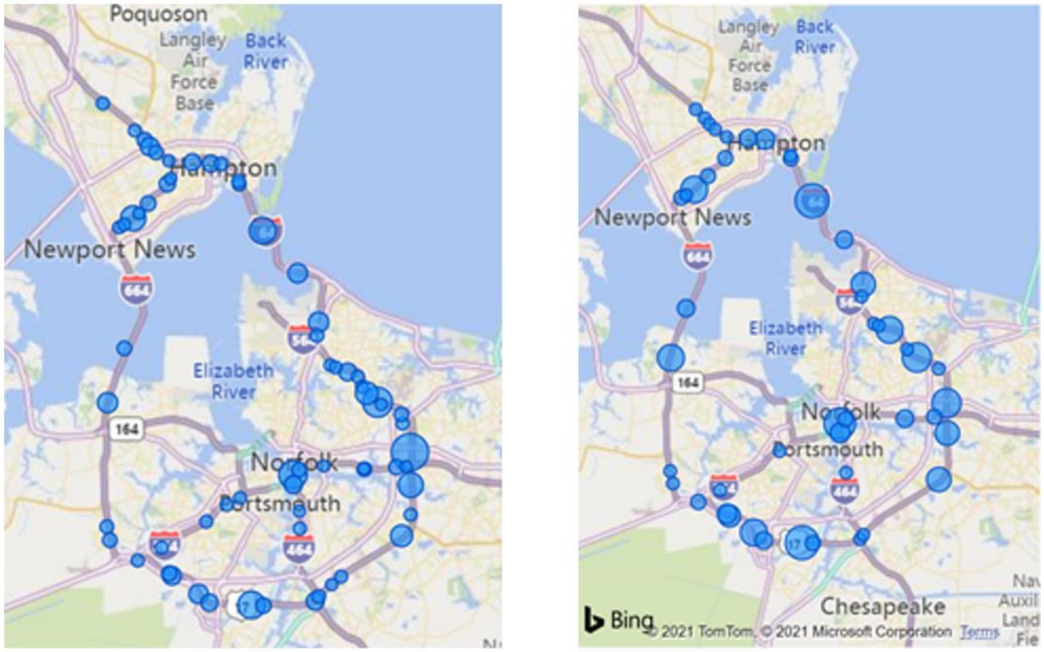
- The expert panel also noted that from the long-range transportation planning perspective (such as Virginia's VTrans), it may be useful to look at such reliability needs (combinations of routes, rather than just one) across the state more carefully before trying to identify appropriate solutions (such as Virginia's SMART SCALE). The panel also noted that metropolitan planning organizations (MPOs) may also find these needs identification useful to compare with their own knowledge of local traffic patterns and that they may have ideas for useful corridor definitions.

- The real-time systemic analysis use case presented by the researchers to the expert panel was as follows: Using a rolling window of last year's systemic PTI values for a link, corridor, and/or network, an analyst could look at the current hour reliability of a link, corridor, and/or network in the context of the previous 1 year. A program code could also be set up to alert the analyst when the current or previous hour(s) was found to be highly unreliable. When discussing the combined analyses of LAFs and detours, as well as the real-time analysis identified by the researchers as a potential use case, the expert panel suggested the possibility of exploring an implementation of these analysis methods by VDOT's Regional Multi-Modal Mobility Program (RM3P) and a need to share these results with the RM3P team.

- The expert panel suggested applying the developed methodology to the VDOT project pipeline process. This process has already identified a number of locations with needs with regard to various transportation goals, including travel time reliability. The application of the new methods developed in this study to these corridors may help the expert panel better understand the strengths and limitations of the new method in comparison to the traditional methods already used by VDOT.

- The expert panel expressed an interest to perform before-after analysis using the new systemic method and measures. In particular, they wondered if a project that does not show link-level benefits might actually show corridor-level benefits.

- A preliminary network-level analysis, as a proof-of-concept example, from Figure 31 was shown to the expert panel as a potential use case. In Figure 31, the bubble size represents the number of hours associated with incidents on each link within the Hampton Roads LAF network. Since some bubbles in Figure 31(a) have disappeared from Figure 31(b), incidents on those links may have a relatively negligible impact on the network reliability. This use case was deemed promising and valuable by the expert panel to pursue further in the future.




**(a)** **(b)**

**Figure 31. Number of Hours Associated With Incidents on Each Link Within the Hampton Roads Network: (a) 2019 AM peak period; (b) top 20 percentile of systemic network travel time.**

4. Research Needs

- The expert panel was particularly interested in why the arterial findings on systemic vs. traditional travel time CDFs were more in line with the a priori expectations than the LAF links. Although the researchers could provide some preliminary suggestions, such as non-homogeneous traffic patterns, signal controls, longer link lengths, etc., these hypotheses could not be tested in this study due to the limited number (73) of detour links in the study network.

- The analysis of link and corridor reliabilities together elicited new and important questions from the panels, such as the following: As we generally look at problems at the link level, is this research suggesting that we would be better off looking at the corridor perspective? How are links and corridors defined? What is the appropriate length of a corridor to look at? The discussion that ensued resulted in two conclusions: (1) both the link-level and corridor-level analyses are useful, depending on the use cases, and (2) guidelines need to be developed for defining corridors and their termini.

- The expert panel specifically asked about the threshold values for link and corridor PTIs used in the screening and if hard thresholds were necessary. Although the researchers stated that some thresholding is necessary, the thresholds are user-definable during the analyses. More research is needed to understand the sensitivity of the results to these thresholds.

Building on the qualitative validation of the soundness of the methods explored in this study and their preliminary results, future studies can conduct a more formal validation such as with the use of a Delphi technique.

## CONCLUSIONS

- *The conclusions presented here should be interpreted and used with due consideration of the limited study network and data limitations described in the "Discussion" section.*

- *Link travel time CDFs constructed by the traditional and systemic methods have a consistent, expected relationship on arterials but not on LAFs. Traditional arterial link travel times were usually higher than the systemic travel times at the higher percentiles and lower at the lower percentiles, consistent with earlier findings on network travel time reliability and travel delays (Lan et al., 2019). On limited access facility links, the 100th percentile systemic travel time was always less than or equal to the 100th percentile traditional travel time, and vice versa at the 0th percentile. At other percentiles, either value was higher than or equal to the other value. Each link must be studied separately to understand these nuanced relationships.*

- *For both the links and the sections, no consistent relationships exist between the systemic and the traditional PTI CDFs. As expected, link LOTTR and travel time CDFs were similar. However, PTI CDFs are strongly affected by the FFTTs (in the denominator of the calculations). Given that a link FFTT and the sum of the FFTTs of the underlying XD segments may be different, direct comparison of the systemic and traditional PTI CDFs for any spatial aggregation is not deemed meaningful.*

- *Systemic analysis of interstate and parallel detour links, as a section, can help identify potential new opportunities for section travel time reliability improvements. Based on the limited study sites, interstate links are usually faster and more reliable than their parallel detour links. Relatively shorter travel times observed for some timestamps on some detour links present new opportunities for section reliability improvement.*

- *PTI CDFs for different links and their parent corridor reveal all four possible reliability relationships across space and time. Some link PTI values were consistently low across all percentiles (highly reliable links) while their parent corridor PTI values were higher at higher percentiles (unreliable corridors). The other three link–parent corridor reliability combinations of reliable-reliable, unreliable-reliable, and unreliable-unreliable were also observed within the study network and the studied dataset. Similarly, some links and their parent corridors exhibited all possible variations of PTI CDFs across multiple years. Knowing the actual relationship for each link-corridor pair can help VDOT understand which links within each corridor are of relatively higher priority to address for improving corridor reliability.*

- *Analyzing timestamped systemic travel time data for links and corridors together presents a valuable spatiotemporal context otherwise not available from the traditional approach.*

*When matched by timestamps, systemic travel times for links and their parent corridors often did not increase together monotonically. In other words, the higher percentile travel times for most links and their parent corridors are often not concurrent. Improving such an unreliable link will likely not improve the corridor reliability.*

- *The systemic network screening method (the Top 20-20 method) identifies links concurrently unreliable with their parent corridor and their upstream-downstream links. To improve a corridor's reliability effectively, all its unreliable upstream-downstream links must be carefully evaluated for combined improvements.*

- *The systemic Top 20-20 method and the traditional individual link network screening method have different strengths. The traditional network screening method is useful in identifying unreliable hotspots. Examples of hotspots include interchanges where the traffic diverts to or comes from another corridor and short corridors with a single link (such as I-195 or I-564).*

- *Applying the causal analysis enabled by the systemic approach (for any spatial aggregation) to links and corridors together, potential solutions for corridor reliability problems can be discovered. In this study, the causes analyzed included spot events such as incidents and work zones (and their potential upstream impacts due to queue spillback) as well as wide area events such as weather events and holidays. Some link-corridor pairs frequently have high travel times concurrent with specific events. Depending on the type of cause and the frequency identified, solutions such as staging of Safety Service Patrol and changes to allowable work hours can be implemented/enhanced.*

- *The analyses using timestamped systemic travel time data require computing resources beyond those available on a typical VDOT personal computer. The timestamped XD travel time data joined with other necessary files require storage space beyond a typical VDOT laptop computer. In this study, additional computing resources (i.e., cloud computing) needed to be employed to execute the analysis.*

## RECOMMENDATIONS

1. *VDOT's TED, OD, and Transportation Mobility and Planning Division (TMPD) and the Office of Intermodal Planning and Investment (OIPI) should use systemic travel time reliability analysis for limited access facility corridors in addition to the traditional analysis whenever causal analyses or upstream-downstream link reliability relationships are of interest.*

2. *VDOT's TED, OD, and TMPD and OIPI should assess the following future research topics and develop research need statements for VTRC or other research groups such as the Transportation Research Board to study:*

- *Exploring systemic travel time reliability concepts on arterial links and sections*. Only 73 arterial links were studied in this project as part of 70 sections. Compared to interstates, data availability and quality on arterial links are usually inferior and traffic conditions are usually more complex due to traffic signals, roundabouts, access points, heterogeneous modes, etc. An understanding of the characteristics and properties of the systemic travel time reliability on arterial links affords further expansion in geographic scope. For example, larger regional networks that include both interstate and arterial links could be examined.

- *Further exploring the systemic travel time reliability concept along corridors and along multiple corridors that serve as mutual detours, beyond just at individual links, based on the systemic reliability*. For example, the Hampton Roads District has two major bridge-tunnels (i.e., on I-64 and on I-664) that provide critical water-crossing service and serve as mutual detour routes in case of road closures. The travel time reliability on those two major routes are therefore expected to have some correlation, which can be explicitly accounted for with the systemic analyses.

- *Expanding the geographic scope of systemic travel time reliability analyses and causal analyses to larger networks.* Whereas links, sections, and corridors are defined by the directional flow of traffic, networks support traffic moving in various directions; a systemic travel time reliability measure should account for multi-direction traffic patterns. Depending on the network size, the causal event types should be restricted. Otherwise, most timestamps will be associated with some causal events on the network.

- *Given that corridor and section definitions are currently subjective, more objective corridor/section termini and detour routes could potentially be defined by clustering links exhibiting similar patterns or trends in travel time reliability.* Some potential drawbacks of this approach include (1) identification of very long corridors in the highly congested urban areas and some very short corridors in rural areas, and (2) the changing of corridor definitions from one year to another.

- *Further exploring the quantification of the potential for reliability improvement on road sections by juxtaposing systemic travel times on interstate and parallel detour links.*

3. *VDOT's TED, OD, and TMPD and OIPI should coordinate with VDOT's Information Technology Division (ITD) to acquire adequate computing resources for timestamp-based analysis.*

## IMPLEMENTATION AND BENEFITS

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

## Implementation

With regard to Recommendation 1, within 3 months of the publication of this report, VDOT's TED and OD and VTRC will meet with Amy McElwain Tang from the RM3P team and Jitender Ramchandani from the VTrans team to present the methodology, results, and potential use cases from this study and document and share their feedback with the TRP. If deemed appropriate based on these meetings, VTRC will assist the TED and the OD in starting to analyze the systemic travel time reliability and the causes (wherever data are available) for no more than 10 select corridors from the project pipeline (selected in conjunction with the TRP) and present the results to the TRP within 9 months after the meetings.

With regard to Recommendation 2, within 3 months of the presentation of the results from the implementation task, VDOT's TED will develop a research needs statement(s) of further interest to VDOT and submit it to the appropriate VTRC research advisory committee or external funding program.

With regard to Recommendation 3, within 2 months of the publication of this report, VTRC will share its experiences on computation needs for the systemic analyses and tools available within VDOT with the TRP.

## Benefits

Recommendation 1 will enable VDOT's TED, OD, and TMPD and OIPI to identify specific use cases of interest for the developed systemic method and transfer the technical knowledge from the researchers to the field practitioners. The systemic travel time reliability method enables explicit identification of causes and upstream/downstream effects that have not been available with the traditional methods. Field experts can develop solutions with more confidence and communicate their findings to the Commonwealth Transportation Board and the public more effectively.

Recommendation 2 will enable VDOT to further the benefits identified by expanding the scope of analysis to networks and by finding economies of scale working with other interested parties.

Implementing Recommendation 3 is a prerequisite for implementing the systemic methodology developed in this study. Staff time and analysis time will be saved significantly by the use of cloud computing.

# ACKNOWLEDGMENTS

The authors thank the technical review panel, the advisory panel, and other professionals for their support including ideas, feedback, data sharing, and analyses. They include Mena Lockwood (VDOT's TED), Margie Ray (OIPI), Katie McCann (VDOT's OD), Jungwook Jun (VDOT's TMPD), Mo Zhao (VTRC), Sanhita Lahiri (VDOT's TED), Simona Babiceanu (VDOT's TED), Matt Bonacci (VDOT's TED), Justice Appiah (VTRC), Mike Fontaine

(VTRC), Jitender Ramchandani (OIPI), Tianye Wang (University of Virginia), Brian Park (University of Virginia), and Mike Massaro (INRIX). The authors also thank the following professionals for their support with information technology / cloud computing: Cathy McGhee (VTRC), Bob Osmond (VDOT's ITD), Mohini Nallapaneni (VDOT's ITD), Lakshmi Ramagiri (VDOT's ITD), Billy Gardner (VDOT's Office of Strategic Innovations (OSI)), Bing Wang (VDOT's OSI), and Mohammad Sharif (VDOT's OSI).

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