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Cost of Congestion Due to Incidents on Freeways

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When alternative incident management strategies are evaluated, there is often a need to convert reductions in incident clearance time to a monetary cost saving. In the past, the Virginia Department of Transportation (VDOT) has used unit delay costs from other agencies to estimate incident congestion costs and the benefit of incident management programs. To improve current practices, congestion cost values developed specifically for Virginia conditions are desired.

This study developed a method to produce planning-level incident congestion cost estimates for interstate highways in Virginia. The per-minute incident congestion costs were estimated using economic, traffic, incident, and roadway data from multiple sources and analyzed at different spatial and temporal aggregation levels. The results showed that the proposed method can produce reasonable estimates of congestion cost at a planning level. The incident congestion costs vary across VDOT districts, routes, time-of-day, and day-of-week; the costs can vary from less than $1 per incident-minute for shoulder-closed incidents in the Bristol District during off-peak hours to $1,347 per minute for lane-blocking incidents in the Northern Virginia District during AM peak hours.

With the variation in costs, the study recommends that corridor-based cost values (where "corridor" is defined as a directional route within a district) be used for analyses of projects across different locations and time periods. The study also recommends that VDOT develop a plan to maintain and update congestion cost values and develop a field-ready App to provide easy access to the congestion cost values for VDOT staff.

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FINAL REPORT

COST OF CONGESTION DUE TO INCIDENTS ON FREEWAYS

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ABSTRACT

When alternative incident management strategies are evaluated, there is often a need to convert reductions in incident clearance time to a monetary cost saving. In the past, the Virginia Department of Transportation (VDOT) has used unit delay costs from other agencies to estimate incident congestion costs and the benefit of incident management programs. To improve current practices, congestion cost values developed specifically for Virginia conditions are desired.

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INTRODUCTION

Traffic incidents are one of the major sources of congestion. The congestion caused by incidents can be reduced by effective incident management. In order to provide a quick response to public requests (e.g., by the Commonwealth Transportation Board), state departments of transportation (DOTs) are often required to perform planning-level cost-effectiveness analyses of incident response strategies and respond within just a few hours. The incident delay cost as a function of the duration of an incident is one of the required elements for assessing the planning-level incident delay cost. The value of travel time has been widely used by agencies to quantify incident delay costs in dollar values. Once the change in traffic delay is calculated, it can be multiplied by the value of travel time to obtain the dollar value of delay. The values of travel time are highly variable, ranging from less than $10 per vehicle-hour to more than $100 per vehicle-hour, mostly because the estimates depend on a number of variables and assumptions (American Association of State Highway and Transportation Officials [AASHTO], 2010; Oregon DOT, 2019a; Victoria Transport Policy Institute, 2020). Due to the differences in the context of travel, highway user characteristics, and vehicle factors, there is no one-size-fits-all value of travel time, and localized values of high quality should be used if available (AASHTO, 2010). The delays caused by incidents also vary by traffic characteristics, roadway geometry, and other factors. Accurate estimates of delay and the value of travel time are obviously important for valuing incident congestion or the performance of incident management programs.

In the past, the Virginia Department of Transportation (VDOT) used the unit cost of incident delay produced by other agencies for planning-level studies. Currently, there are no standard congestion cost values used in a consistent manner VDOT-wide to communicate incident management results. Given that the traffic demand patterns and socioeconomic activities vary among different states and can change over time, it is imperative to develop Virginia-specific cost values and keep the values current.

PURPOSE AND SCOPE

The purpose of this study was to estimate the planning-level aggregated congestion cost due to incidents on Virginia interstates. The congestion cost estimates could be used to convert reductions in roadway clearance time to a monetary value, which provides the basis for cost-benefit analysis among different incident response strategies.

The objectives were as follows:

- Perform an economic analysis to determine the unit value of travel time per vehicle type and trip purpose.
- Develop a practical method for estimating delays and costs caused by incidents on interstates.
- Create a table of planning-level estimates of incident congestion cost as a decision support tool.

The scope of the study was limited to Virginia interstates and did not extend to the impact on the network of arterial roads that provide access to and from the interstates. The aggregated cost values provided at the planning level should not be used to evaluate individual incidents.

METHODS

The following tasks were performed to achieve the study objectives.

1. Conduct a literature review.
2. Collect and prepare data.
3. Estimate the value of travel time.
4. Analyze incident probabilities and durations.
5. Estimate the delay and cost due to incidents.

Literature Review

A review of the literature was conducted to summarize research on the topics of the valuation of travel time and incident congestion. Scientific research articles and publications from government agencies, universities, and consulting companies were reviewed through searches of Google Scholar, the TRID database, and forward and backward citations of relevant articles.

Collect and Prepare Data

This study considered various aspects of data that could affect the estimation of congestion costs, including economic data, incidents, traffic demand, speed, roadway capacity, and lane configuration. Details on the data used and their preparation are discussed here.

Description of the Study Network

The study network consisted of all Virginia interstates, consisting of nearly 2,230 directional miles (see Figure 1). The primary spatial analysis unit in this study was a "link" used by VDOT's Operations Division for many operational analyses. An interstate "link" is defined as a directional stretch of roadway between two adjacent exits. The link definition files were obtained from the Operations Division, verified using ESRI ArcGIS and Tableau, and manually updated as needed. A "corridor" is defined as a directional stretch of an interstate containing several contiguous links within a VDOT district. Table 1 shows the details of these two different spatial segments.

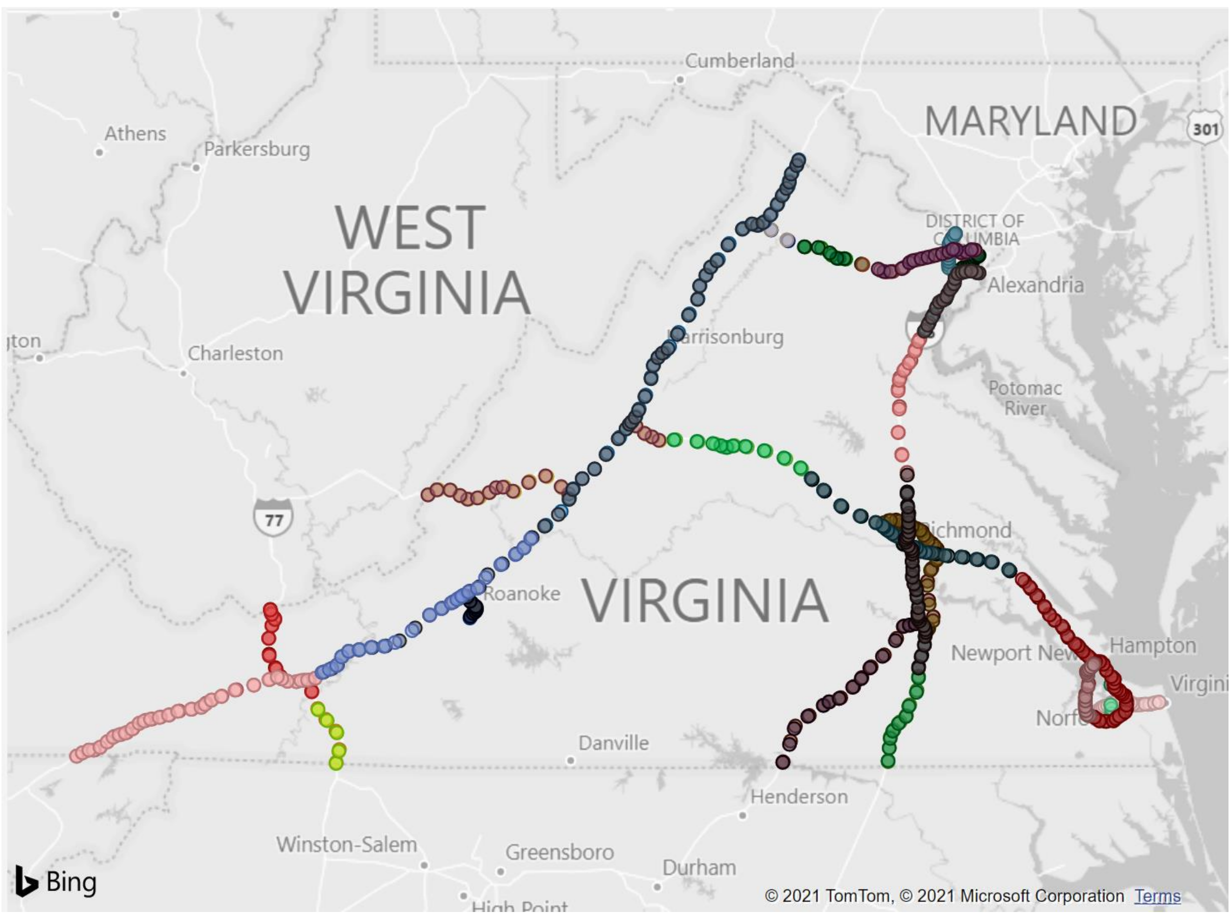

Figure 1. Study Network With Link Mid-points Shown as Dots and Corridors Indicated Using the Dot Color

Table 1. Features of Spatial Segmentations Used in This Study

Segmentation Type	No. of Elements	Average Length (mi)	Length Range (mi)
Link	767	2.91	0.17-11.7
Corridor	53	42.86	1.98-149.13

Data Types and Sources

The following sections introduce the data sources and the preparation process.

Economic Data

The economic data used included the following:

- value-of-time to hourly earnings ratio from the U.S. Department of Transportation (U.S. DOT) (U.S. DOT, 2016)
- hourly earnings of truck drivers from the U.S. DOT (U.S. DOT, 2016)
- average vehicle occupancies from the Federal Highway Administration (FHWA) (FHWA, 2019)
- fraction of trip purpose in traffic from the U.S. DOT (U.S. DOT, 2016)
- Consumer Price Index and hourly wages from the Bureau of Labor Statistics (2021)
- truck operating cost from the American Transportation Research Institute (ATRI) (ATRI, 2020).

One objective of this study was to adopt Virginia-specific data to the extent possible. Published information from national sources and sources in other states were consulted for purposes of comparison. Default values for those data were included in the spreadsheet as a part of the final deliverable.

Incidents

Interstate event data from 2017-2020 were obtained from VaTraffic. VaTraffic is a VDOT operations and incident management database that provides information on various activities, which include all known abnormal road and traffic conditions; road closures, whether caused by traffic incidents, maintenance, work zones, or weather events, are reported by the traffic operation centers, VDOT staff, or contractors. Incident event attributes available and relevant to this study include the timestamps for incident start, clearance, and closure; latitudes and longitudes of the event; road name; route number; direction; mile marker; and number of lanes closed. Interstate events were conflated to the links using the start/end mile markers.

Traffic Demand

Traffic demand is an essential input in determining traffic queue, delay, and secondary incident probabilities; the demands can vary across different links, time-of-day, and day-of-week. VDOT's Traffic Engineering Division provided annual average daily traffic (AADT) estimated from both continuous and short-term count stations. AADT and average volume profile factors for each day-of-week and hour were obtained for each Traffic Message Channel (TMC) segment from VDOT's Operations Division and VDOT's Traffic Engineering Division. The TMC AADT was multiplied by the volume profile factors to obtain estimated hourly traffic volumes.

The average truck percentage by TMC for 2019 was obtained from the National Performance Management Research Dataset (NPMRDS). Since the study network includes only interstates, all of which are covered by the NPMRDS, the NPMRDS and level of aggregation were sufficient for this study.

These data were conflated from TMCs to links using a TMC-link crosswalk table. For any timestamp, link volumes by both passenger cars and trucks were calculated as the length-weighted average of the volumes and truck percentages of the constituent TMC segments.

Link Capacity

VDOT's Traffic Engineering Division provided link capacity estimates for each TMC. The link capacities were calculated as the length-weighted average of the constituent TMC segments. Equations 1 and 2 from the *Highway Capacity Manual Sixth Edition* (Transportation Research Board, 2016), hereinafter "HCM 2016," were used to estimate link capacity when TMC-based values were not available.

$$Base\ capacity = 2{,}200 + 10 \times (FFS - 50) \quad \text{[Eq. 1]}$$

$$Capacity = Base\ capacity\ \times Lanes \times f_{hv} \times PHF \times f_p \times f_g \quad \text{[Eq. 2]}$$

where

FFS = link free-flow speed
f_{hv} = heavy vehicle adjustment factor
PHF = peak hour factor
f_p = driver population factor
f_g = grade factor.

Link Free-Flow Speed

The literature frequently refers to free-flow speed at a location as the 85th percentile speed from some time period when the traffic is low (Schrank et al., 2015; U.S. DOT, 2020). Schrank et al. (2015) used the nighttime hours of 2200 to 0459 and the FHWA (2020) used the daytime hours of 0900 to 1559 and 1900 to 2159 for Monday through Friday and 0600 to 2159 for Saturday and Sunday.

The free-flow speed in this study was derived from speed data from a third party vendor, INRIX. Python codes were developed to download the data using the INRIX data download APIs. The INRIX data were conflated to links using a crosswalk table. For each link, the travel time at a timestamp was calculated as the instantaneous link travel time (Xiao et al., 2014). This study calculated free-flow speed using the 2016-2019 dataset after excluding incident and work zone events: the period of 10 AM to 4 PM was used.

Number of Lanes

The number of lanes at each link was obtained from the Open Source Maps (OSM) web repository (OSM, n.d.); Google Street View was used in conjunction with OSM to verify the field conditions and to determine the number of lanes manually. In this study, only interstate main lanes were counted in the number of lanes; other types of lanes, e.g., auxiliary lanes and truck climbing lanes, were not included.

Data Quality Checks

The 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. Traffic incidents were screened to remove outliers, including records with end time earlier than start time, incident durations less than 5 minutes or more than 24 hours, and number of lanes closed that was greater than the total number of lanes.

Hourly traffic profiles were also inspected to remove unreasonable values. To be more specific, when an hourly traffic factor showed a value larger than 1, it was removed and replaced with the average of hourly factors from the previous hour and the following hour.

Estimate Value of Travel Time

This study incorporated most information about the travelers' value of time in an equation of the form of Equation 3:

$$VoT = (PL_1/PL_0) \times (INC_1/INC_0) \times \sum(R_i \times HE_i \times AO_i \times F_i) \quad \text{[Eq. 3]}$$

where

(VoT) = travelers' value of time

PL_1 = prevailing price level at time of analysis

PL_0 = baseline price level at time when value-of-time values were estimated

INC_1 = prevailing income level at time of analysis

INC_0 = baseline income level at time when value-of-time values were estimated

R_i = ratio of the value of time for travelers in traffic category i and hourly earnings for travelers in traffic category i

HE_i = average hourly earnings of travelers in traffic category i

AO_i = average occupancy of vehicles in traffic category i as a fraction of total throughput flow on route under study

i = subscript that indexes the categories of traffic.

The default values of PL_1 and PL_0 were set using the Consumer Price Index from the Bureau of Labor Statistics for the target year (Bureau of Labor of Statistics, 2021) and the base year (2015). The default values of INC_1 and INC_0 were set to $28.92 and $27.20, the average hourly earnings in Virginia and in the United States, respectively, in 2020. These parameters offer the analyst the opportunity to make an adjustment to account for inflation or for a different regional level of average income. These numbers will scale the value-of-time computation up or down only if the user selects study-specific information that makes either of these ratios, PL_1/PL_0 or INC_1/INC_0, equal something other than 1.00.

The default values of the value of time– to–hourly earnings ratios (R_i) are drawn from the U.S. DOT guidance (U.S. DOT, 2016). The default values of the average hourly earnings (HE_i) are also drawn from the U.S. DOT guidance. An analyst who has detailed earnings data for the neighborhood of the route under study may choose to set earnings different from the defaults. The default values of the average vehicle occupancies (AO_i) are drawn from the 2017 National Household Travel Survey (U.S. DOT, 2020).

A spreadsheet tool was developed that provided two alternative sets of default values for each travel category as fractions of the total throughput flow on the route: one set of values estimated for local (short-distance) travel, and one set of values estimated for intercity (long-distance) travel; each set was drawn from the literature as reported in the literature review. Five distinct travel categories were identified in this study: (1) local travel for personal purposes in passenger cars, (2) intercity travel for personal purposes in passenger cars, (3) travel for business purposes in passenger cars, (4) travel for business purposes in trucks, and (5) travel in buses. An analyst who has specific information about the traffic mix on the route he or she is studying will likely choose to throughput flow fractions different from the defaults; the analyst may also choose to define travel categories and vehicle types different from the defaults.

In this study, the passenger car and truck values of time were computed with the set of default values for intercity travel. The bus value of time was not considered in the interstate congestion cost estimation; it could have more use in estimating intra-city congestion cost.

Analyze Incident Probabilities and Durations

Descriptive analyses were performed to study traffic incident distributions and durations at various aggregation levels. Events due to construction and maintenance work zones and severe weather were excluded from the dataset. Here, "incident duration" is defined as the time from the first notification of the incident to the time when all travel lanes are cleared. Although this is not perfect, it was deemed appropriate for the purposes of this study. The incident distributions and durations calculated with VaTraffic data were compared to the mean distributions of freeway incidents and the default incident duration parameters in HCM 2016 (Transportation Research Board, 2016) in terms of mean absolute difference to identify the probabilities and mean durations that best fit the planning-level estimates of incident congestion delay.

Incidents on interstates could cause additional incidents near existing incident locations due to unexpected congestion or rubbernecking, which further increases traffic delay. "Secondary incidents" are defined as incidents occurring as a result of earlier incidents either within the incident scene or within the queue in either travel direction. The probability of a secondary incident is estimated using the following model (Eq. 4) developed by Goodall (2017) using data collected on the entire length of I-66.

$$P(s) = \frac{e^Y}{1+e^Y} \quad \text{[Eq. 4]}$$

where

$P(s)$ = probability of secondary incident occurring

$$Y = \begin{Bmatrix} -4.459 + 0.006985t + 0.000162d \; for \; C = 0; \\ -2.836 + 0.006985t + 000162d \; for \; C = 1 \end{Bmatrix}$$

C = 1 for congestion

t = incident duration in minutes

d = total number of vehicles that encountered incident or its queue.

In this study, "congestion" is defined as any analysis interval during which the estimated demand is greater or equal to the estimated capacity. The probability of a secondary incident occurring was estimated for each link, incident type (shoulder closure, one-lane closure, and so on), and analysis interval. The estimated secondary incident probabilities were then multiplied by the aggregate incident congestion cost to obtain the average secondary incident costs for each link, incident type, and analysis interval. This approach provided a simple cost estimate at the planning level and was not intended to predict explicitly the characteristics and the impact of secondary incidents. Due to their low probability, secondary incidents are not expected to affect considerably the average incident congestion cost on a link.

Estimate Delay and Cost Due to Incidents

The incident congestion costs were estimated with three major components: (1) the value of time, (2) the incident probability (including the secondary incident probability), and (3) the estimated traffic delay caused by incidents. A simple overview of the proposed delay and cost estimation framework is presented in Figure 2. The traffic delay, as well as the associated cost, was first calculated for each link, time-of-day, and day-of-week, which were then aggregated at varying spatial and temporal levels for further analysis.

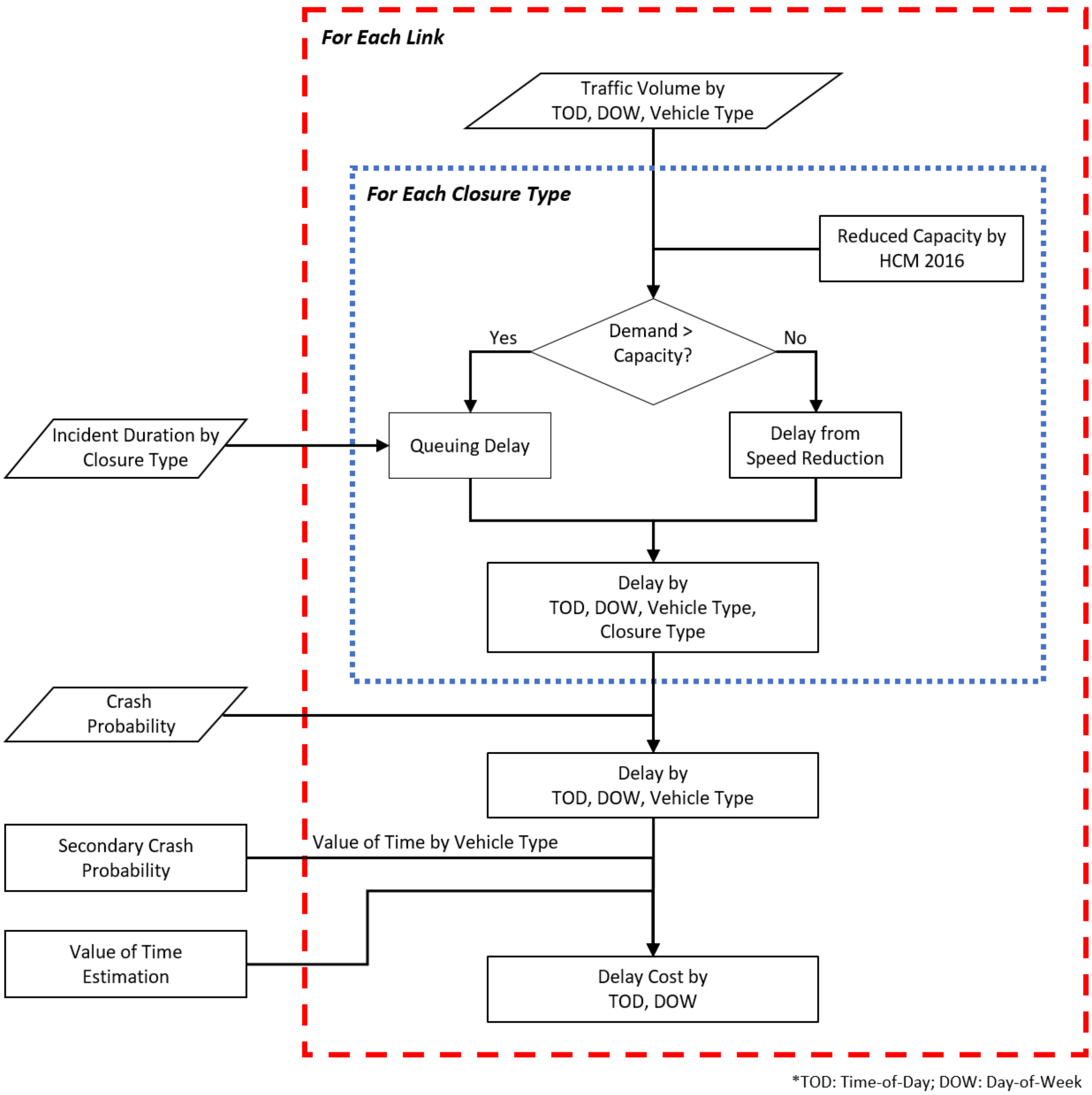

Figure 2. Computation Framework for Estimating Incident Congestion Costs on Interstates

First, the traffic delay was estimated for each closure type (e.g., shoulder-only, one-lane closed) from the start of an incident until all travel lanes were open (if no traffic queue existed at the end of the incident) or the queue fully dissipated. Inputs considered in the delay estimation included (1) the time-dependent (time-of-day and day-of-week) traffic demand throughout the entire queue evolution; (2) the average incident duration for each closure type; and (3) the reduced capacity under each closure type. Second, the estimated traffic delay (by vehicle type and by closure type) was divided by the incident duration (by closure type) to derive the delay per incident-minute by vehicle type and by closure type. Third, the secondary incident probabilities under different closure types of primary incidents were introduced to account for the potential delay increases caused by secondary incidents. Fourth, the value-of-time (by vehicle type) component was brought in to convert delay per incident-minute into a monetary value. Fifth, the delay costs under different closure types by link, time-of-day, and day-of-week were aggregated at user-defined spatial and temporal levels for further analysis. The aggregated delay (and cost) values were calculated as the incident-frequency weighted average of the delays (and costs) by closure type. Details for major components in the estimation process are discussed in the following subsections.

Link Capacity Drop Due to Incident Lane Closures

Interstate incidents can result in blockages ranging from shoulder-only, one-lane, to multiple-lane closures. The number of blocked lanes significantly affects the link capacity during the incident and will create a traffic queue when traffic demand exceeds the reduced capacity. A set of deterministic capacity adjustment factors in HCM 2016 (Transportation Research Board, 2016) were adopted to calculate the capacity drop and thus the reduced capacity (see Table 2). Each element in Table 2 represents the proportion of lane capacity remaining while the lane blockage is present; these values were applied to the lanes that remained open during the incident.

Table 2. Capacity Reduction Factor per Lane in Incident Zones per HCM 2016

No. of Lanes (One Direction) Before Incident	Shoulder Closed	One Lane Blocked	Two Lanes Blocked	Three Lanes Blocked	Four Lanes Blocked
2	0.81	0.70	N/A	N/A	N/A
3	0.83	0.74	0.51	N/A	N/A
4	0.85	0.77	0.50	0.52	N/A
5	0.87	0.81	0.67	0.50	0.50
6	0.89	0.85	0.75	0.52	0.52
7	0.91	0.88	0.80	0.63	0.63
8	0.93	0.89	0.84	0.66	0.66

HCM 2016 = *Highway Capacity Manual,* Sixth Edition (Transportation Research Board, 2016); N/A = Not Available**.**

Delay Estimation

With the determination of reduced capacity caused by lane blockages, two distinct traffic states can be distinguished: (1) when demand exceeds the reduced capacity, and (2) when demand is under the reduced capacity. Traffic delay under the first condition is assumed to be mainly queuing delay, and that under the second condition is assumed to be caused by speed reduction.

Estimation of Queuing Delay

A queue evolution model (see Eq. 5) was introduced to estimate the number of vehicles in the queue at each timestamp; the number of vehicles by type (cars and trucks) was calculated by multiplying the corresponding proportion values.

The delay at each timestamp was calculated by multiplying the number of vehicles in the queue by the time step size (which was set to 1 minute in this study). The total queuing delay for an incident was then calculated by summing the delay at all timestamps from the start of an incident until the queue fully dissipated; the queue duration can often be significantly longer than the incident duration. It should be noted that the proposed queue estimation method is a simplification, as the incident response team often moves vehicles involved in a lane-blocking incident to the shoulder and opens up the lane for traffic prior to the complete clearance of the incident. With this simplification, the link capacity was assumed to have returned to full capacity after all travel lanes were open (see Eq. 5).

$$Q(i) = Q(i-1) + V(i) - C\ (i) \qquad \text{[Eq. 5]}$$

where

$Q(i)$ = number of vehicles in queue at end of the i-th minute
$Q(i-1)$ = number of vehicles in queue at end of the (i -1)-th minute
$V(i)$ = number of vehicles arrived during the i-th minute
$C\ (i)$ = reduced capacity during the i-th minute.

Estimation of Speed Reduction Delay

Link speeds under incident conditions were estimated using Equation 6 (Equation 25-1 in the *Highway Capacity Manual*, Fifth Edition (Transportation Research Board, 2010) in combination with the capacity reduction factors given in Table 2 (Zegeer et al., 2014).

$$S = FFS + \left[1 - e^{\left(ln\left(FFS+1-{C\times CAF}/_{45}\right)\times {v_p}/_{C\times CAF}\right)}\right] \qquad \text{[Eq. 6]}$$

where

S = link speed
FFS = link free-flow speed
C = original link capacity (pcphpl)
v_p = link flow rate (pcphpl).

Link travel times under free-flow speed and incident conditions were compared to estimate the delay due to speed reduction. This approach may overestimate the speed reduction delay due to incidents as it cannot differentiate the delay caused by recurring congestion.

Speed reduction delay is calculated only for the analysis intervals during which no queues are accumulated (estimated demand < estimated capacity) on a link. When a queue exists, queueing delay is estimated using the method described in the queuing delay subsection.

RESULTS AND DISCUSSION

Literature Review

This section reviews the literature pertaining to the value of travel time and the delay cost due to traffic incidents.

Value of Travel Time

A Default Average Value of Time

The U.S. DOT published a memorandum in 2014 entitled "Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis" (Ayala, 2014); an update 2 years later offered dollar estimates at Year 2015 prices in lieu of the 2012 estimates in the previous memorandum (U.S. DOT, 2016). The guidance recommended that travel time for local travel by all surface modes be valued at 50% of the average earnings per person-hour when the travel is for personal purposes and that the travel time for intercity travel by all surface modes be valued at 70% of the average earnings per person-hour when the travel is for personal purposes (U.S. DOT, 2016). The guidance also recommended that travel time for all business travel (including the time of all vehicle operators) be valued at 100% of the average earnings per hour. Since the guidance estimated that business purposes accounted for 4.6% of local travel and 21.4% of intercity travel by surface modes, the amount equates to a recommendation that travel time for local travel be valued at 52.3% of the average earnings per hour and travel time for intercity travel be valued at 76.42% of the average earnings per hour. The guidance then relaxed these assumptions, identifying "plausible ranges" for travel by surface modes for personal purposes as 35% to 60% of hourly earnings for local travel and 60% to 90% for intercity travel while identifying "plausible ranges" for travel by surface modes on business as 80% to 120% (U.S. DOT, 2016). The guidance recommended, in conclusion, an average travel time value of $14.10 per hour for local travel by surface modes, with a plausible range of $10.00 to $17.00, and $20.40 per hour for intercity travel, with a plausible range of $17.20 to $25.80. These dollar figures are expressed at Year 2015 prices.

Adjustments to the Value of Time to Reflect Additional Information

When additional information—about either the composition of traffic, the local economic conditions, or time-of-day—is available, the analyst may be able to refine the value of time used in the analysis to reflect that additional information.

Adjustments to Reflect Trip Purpose. The U.S. DOT guidance (U.S. DOT, 2016) drew a distinction between travel for personal purposes and travel for business purposes. The guidance recommended a default value of time of $14.10 per hour for local surface travel and $20.40 per hour for intercity surface travel when the trip purposes are unknown.

The guidance also specified distinct values for personal travel and business travel. For local personal travel, the recommended value was $13.60, with a plausible range of $9.50 to $16.30; for intercity personal travel, the recommended value was $19.00, with a plausible range of $16.30 to $24.50 for intercity travel.

For business travel, the recommended values were $25.40, with a plausible range of $20.30 to $30.50.

Adjustments to Reflect Vehicle Mix. When traffic counts are distinguished between passenger cars and trucks, the U.S. DOT guidance makes it possible for the analyst to assign a more precise, modified value of time. For truck drivers, the U.S. DOT guidance recommended a value of time of $27.20 per hour, with a plausible range of $21.80 to $32.70 (U.S. DOT, 2016).

In the U.S. DOT guidance, a global value of time was calculated based on vehicle mix, whereas in this study, the value of time was developed specifically for each vehicle type. The developed value of time was used in conjunction with traffic delays by vehicle type on each link and resulted in a better delay cost representation.

Adjustments to Distinguish Between Local Traffic and Through Traffic: Value of Time as a Function of Trip Distance. The U.S. DOT guidance drew a distinction between local travel and intercity travel (U.S. DOT, 2016). This distinction may be relevant when the analyst is able to identify the route under study as a road that carries mostly "local" traffic or a road that carries a large portion of "through" traffic. When it is possible for the analyst to judge whether the traffic on the route in question is "local" or "intercity" or to estimate what percentage of the flow falls into each of these categories, the U.S. DOT guidance makes it possible for the analyst to assign a more precise, modified value of time to the vehicles on that route.

Adjustments to Reflect Time of Day. A few authors have reported separate value-of-time estimates for two or more periods of the day (Paleti et al., 2015; Tseng and Verhoef, 2008). Differences in the value of time of the average traveler from one period or another may have to do with the scheduling of group activities (schooling, work shifts) that require certain types of persons to be traveling—or not traveling—at roughly the same time. Differences in the average value of time from one period to another may also result from temporal self-sorting analogous to the spatial self-sorting described previously concerning toll roads. An analyst studying a policy that has a differential impact at certain periods of the day might attempt to adjust the value of time to reflect this.

Because of the data availability for this study, the researchers do not recommend accounting for differences due to activities in time-of-day or day-of-week. The delay cost differences were considered with the traffic volume estimates.

Adjustments to the Value of Time Due to Price Changes or Income Changes

A comparison between the real incomes of two travelers (or two groups of travelers) at the same point in time differs conceptually from a comparison between the nominal incomes of a traveler (or a group of travelers) at two points in time. For practical purposes, however, the benefit/cost analyst may not have sufficiently detailed information to approach these two cases any differently from each another. Whether the change in income is real or nominal, one might expect the average traveler's value of time to rise proportionately as hourly earnings or Gross Domestic Product per capita rises from either region to region or year to year.

Adjustments for Inflation. When the analyst makes use of a value-of-time estimate that is old enough to have become virtually obsolete because of inflation, the analyst must nonetheless expect to make an inflation adjustment.

Published findings do not make a strong case that the average traveler's value of time has evolved over time in lockstep with the mean hourly wage or with the cost of living (Goodwin, 2019; Quient and Meunier, 2014). For one thing, the state of the art in estimating the traveler's value of time has also evolved over time. For another thing, the changes in amenities as safety, comfort, and access to telecommunications make the experience of an hour of travel time today different from the experience of decades past.

Short of revising the values of time on the basis of more recently published studies, however, the most straightforward first-order approximation is the assumption that a change in wages and prices—i.e., inflation—will have a one-to-one impact on the traveler's value of time.

Regional Heterogeneity: Value of Time as a Function of Income. The average hourly earnings in the region where the route in question runs offers another opportunity to assign a more precise, modified value of time. Meunier (2020) observed that published findings in France suggested that the elasticity of the value of time with respect to income is about 0.7 to significantly less than 1.0. Meunier stated, however, that benefit/cost analysts in many countries of the Organisation for Economic Co-operation and Development routinely assume an elasticity of 1.0 and assign a value of time accordingly.

The U.S. DOT guidance weighed the arguments for and against the assumption of unitary elasticity with respect to income and came down in favor of it (U.S. DOT, 2016).

Vehicle Operating Costs

ATRI conducts an annual survey of their members to determine the estimates of truck operating costs. The ATRI operating cost survey categorizes costs into two major categories: vehicle-based, and driver-based. Vehicle-based cost variables include fuel, truck/trailer lease or purchase payments, repair and maintenance, insurance premiums, tires, and tolls whereas driver-based cost variables include driver wages and benefits. Given that the driver-based value of time has been accounted for using Equation 3 with Virginia values, the vehicle-based marginal costs per hour for trucks were derived from Table 9 in the ATRI 2020 report (ATRI, 2020).

The operation cost based on passenger car time was derived from the TRB Economics Committee and includes vehicles' tire, maintenance, and depreciation; it was set to $5.02 per hour. The U.S. Department of Energy (2015) suggested that the passenger car idling fuel usage ranged from 0.16 to 0.39 gallons per hour; the Virginia average gas price was set to $3.105 per gallon (AAA, 2021). With the idling fuel usage set to 0.275 gallon per hour and the average gas price, the passenger car idling fuel cost was set to $0.85 per hour. The passenger car marginal cost per hour was therefore set to $5.87 per hour.

Incident Congestion Cost

The value of travel time has been used by many state DOTs for evaluating incident response procedures, but few DOTs have published aggregated incident/lane closure costs for agency-wide business analyses. The Oregon DOT estimated hourly delay cost due to unexpected highway closures using values of travel time and traffic volumes from automatic traffic recorders (Oregon DOT, 2019b). The hourly delay costs are provided for each automatic traffic recorder location by traffic volume level (average, low, high, peak hour). These delay costs, ranging from $100 per hour in the lowest volume condition to $332,600 per hour in the highest volume condition, apply to full-roadway-closure scenarios. The values of travel time used to estimate the closure costs included $26.44 per hour for auto and light trucks; $31.89 per hour for delivery and medium trucks; and $33.24 per hour for heavy trucks.

The Washington State DOT's *Handbook for Corridor Capacity Evaluation* (Washington State DOT, 2016) uses delay costs of $244 per minute for non-blocking incidents and $345 per minute for lane-blocking incidents for incident response analysis. The values of travel time used to produce these delay costs were $21.90 per hour for passenger cars and $57.40 for trucks from a Washington State DOT study in 2009 reported by Hallenbeck et al. (2011).

The delay cost of $345 per minute for lane-blocking incidents developed by the Washington State DOT was adopted in a study to evaluate the contract towing and first responder pilot projects on I-81 in VDOT's Staunton District (Dougald and Venkatanarayana, 2017). The average incident duration savings was estimated by Equation 7:

Average incident duration savings = Average incident duration reduction × Average delay cost ($345 per minute of lane closure) [Eq. 7]

Dougald and Venkatanarayana suggested a method for estimating average lane clearance time savings, which used a different unit delay cost of \$32.90 per vehicle-hour, was also used in the I-81 study for comparison (Dougald and Venkatanarayana, 2017). The value of \$32.90 was estimated based on \$16.72 per vehicle-hour for passenger cars and \$86.81 per vehicle-hour for commercial trucks. The average lane clearance time savings was estimated by Equation 8:

Average lane clearance time savings = Average lane clearance time saved × 4 minutes of delay per 1 minute of lane blockage × Average delay cost (\$32.90 per vehicle-hour) [Eq. 8]

The benefit/cost ratio (11.8) calculated using the method based on average incident duration savings was smaller than that (18.1) using the method based on average lane clearance time savings, but both methods justified the feasibility of the projects (Dougald and Venkatanarayana, 2017). In practice, agencies often do not have the values of travel time at the desired level of detail. The feasibility analysis would give a determination whether a project remained feasible or infeasible regardless of the values of travel time used (AASHTO, 2010).

Incident Probabilities and Durations

Incident data from 2017-2020 were used to study traffic incident distributions and durations. Among the 341,523 incidents, about 20% (68,823) caused the closure of at least one travel lane. The rest, mostly incidents involving disabled vehicles, were considered shoulder-closure incidents (number of lanes closed = 0).

Probabilities and Average Durations

Incident probabilities by lane closure type and VDOT district were calculated and are shown in Figure 3. The trend of incident distributions by lane closure type was similar on interstates across the state. Generally, the probability of incidents decreased as the number of lanes closed increased. The districts of Culpeper, Hampton Roads, and Staunton used an incident logging system different from that of the other parts of the state, and many shoulder-closure incidents were not recorded in their systems; therefore, the probability of shoulder-closure incidents was shown to be lower than that of one-lane-closure incidents for those districts.

The incident probabilities in the study periods were compared to the mean distributions of freeway incidents in HCM 2016 (Transportation Research Board, 2016). As shown in Table 3, the probabilities under each lane closure type for the study area were similar to the HCM 2016 values. The maximum absolute difference between the 4-year average and the corresponding HCM value was 0.038 (two-lane closure incident).

The mean incident durations by lane closure type were also calculated and compared with the default values in HCM 2016. From Table 4, the differences between the 4-year average durations and the HCM 2016 values were within 3.3 minutes for incidents with two or fewer lanes closed. The average durations of incidents with three or four lanes closed were higher than the HCM 2016 values.

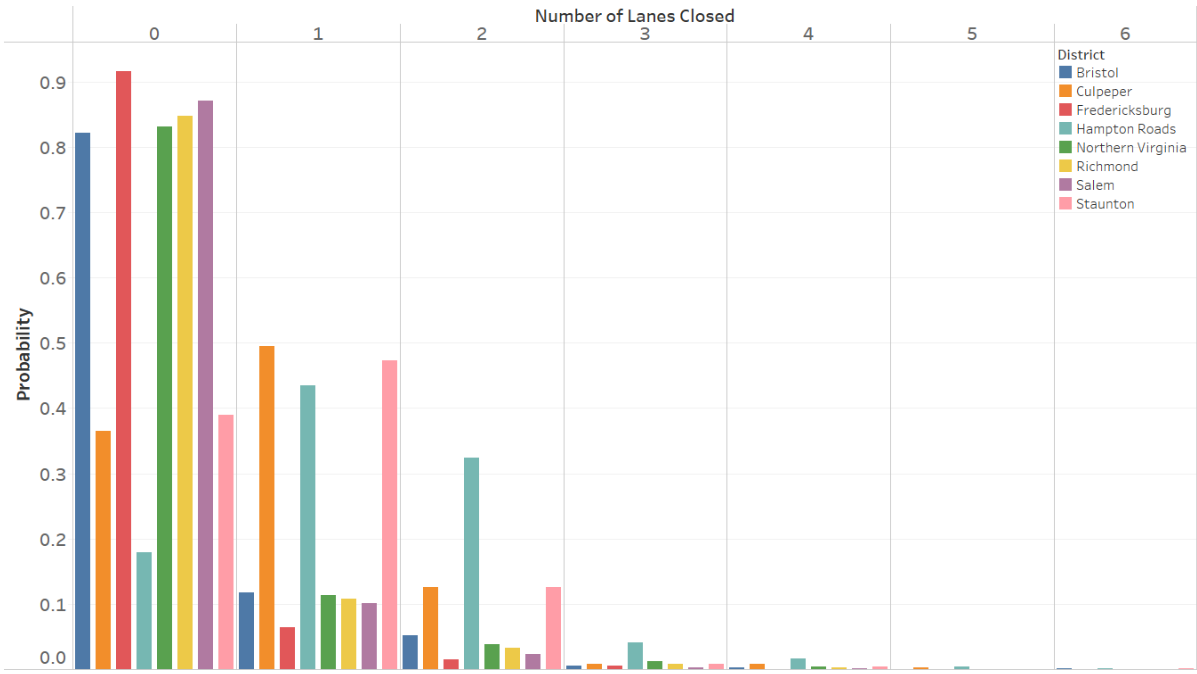

Figure 3. Probabilities of Incident by District and Number of Lanes Closed

Table 3. Incident Probabilities From VaTraffic Data and HCM 2016

No. of Lanes Closed	Incident Probabilities					
	2017	2018	2019	2020	Average	HCM 2016
0	0.750	0.755	0.748	0.734	0.747	**0.754**
1	0.162	0.162	0.168	0.168	0.165	**0.196**
2	0.070	0.066	0.066	0.075	0.069	**0.031**
3	0.013	0.012	0.013	0.016	0.014	**0.019**
4	0.004	0.004	0.004	0.006	0.005	**0**
5	0.001	0.001	0.001	0.001	0.001	**0**
6	0.000	0.000	0.000	0.000	0.000	**0**

HCM 2016 = *Highway Capacity Manual*, Sixth Edition (Transportation Research Board, 2016).
Values in bold type indicate values in HCM 2016.

Table 4. Mean Incident Durations From VaTraffic Data and HCM 2016

No. of Lanes Closed	Incident Duration (min)					
	2017	2018	2019	2020	Average	HCM 2016
0	26.7	30.9	37.2	33.6	32.1	**34**
1	35.2	37.7	37.7	40.9	37.9	**34.6**
2	47.7	52.5	50.2	51.8	50.5	**53.6**
3	77.8	74.1	71.0	78.0	75.2	**67.9**
4	90.5	94.1	84.8	87.8	89.3	**67.9**

HCM 2016 = *Highway Capacity Manual*, Sixth Edition (Transportation Research Board, 2016).
Values in bold indicate values in HCM 2016.

Since the calculated incident probabilities and durations were quite close to the default values in HCM 2016, the researchers decided in conjunction with the technical review panel for this study to use the default values in HCM 2016 for estimating incident congestion costs at the planning level.

Probabilities of Secondary Incidents

The probability of a secondary incident was estimated for each link, lane closure type, and analysis interval. These probabilities were used to calculate the additional costs due to secondary incidents. The estimated probability by number of lanes closed is shown in Figure 4. The probability of a secondary incident increased significantly when two or more lanes were closed. For incidents with three or four lanes closed, the probability of a secondary incident was higher than 12%. It should be noted that the model for estimating the probabilities of secondary incidents was developed using data for I-66 in the Northern Virginia District and was not validated for other routes; in the I-66 dataset, the probability of a secondary incident on average was about 1.9% for incidents of disabled vehicles, 10% for crashes, and 13% for incidents of vehicle fires (Goodall, 2017). The probability of a secondary incident estimated in this study was 1.76% for shoulder-closure incidents, which is close to the 1.9% and 1.5% for disabled vehicle incidents found in the I-66 study and a Hampton Roads area study (Khattak et al., 2011), respectively.

Because of the differences in lane configuration, the same number of lanes closed at different links could affect the link capacities very differently. The estimated probability of a secondary incident by the proportion of lanes closed is given in Figure 5. The probability of a secondary incident tends to increase with the proportion of lanes closed but not monotonically. When the portion of lanes closed is the same, links with a higher total number of lanes, and higher volume, too, have a higher probability of a secondary incident.

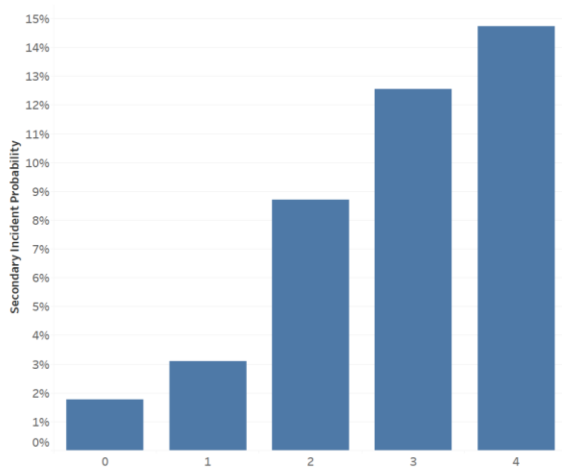

Figure 4. Estimated Secondary Incident Probability by Number of Travel Lanes Closed

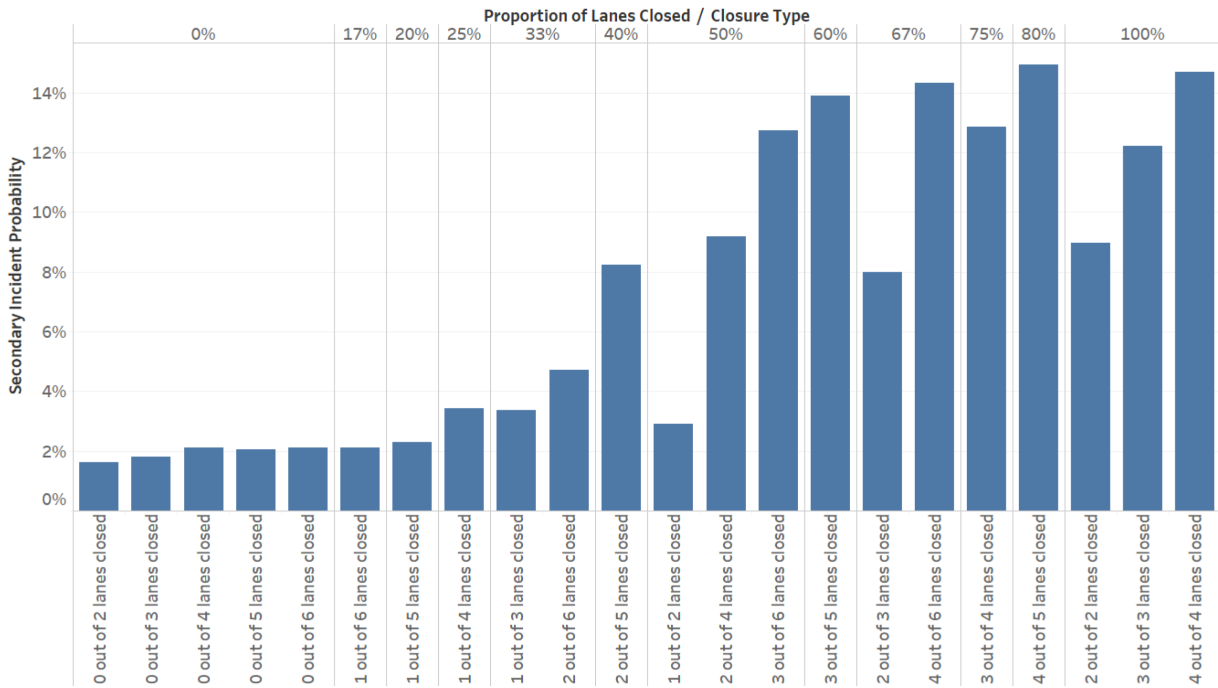

Figure 5. Estimated Secondary Incident Probability by Proportion of Travel Lanes Closed. Note: 0 lane closed = shoulder closure.

Incident Congestion Cost

Incident Congestion Cost Aggregated at State and District Levels

The incident congestion costs were analyzed at the state and district levels to provide an overview of cost values. Table 5 shows a comparison of the incident congestion cost per incident-minute among different districts; the statewide average values are shown in the last row.

Each row in each sub-table in Table 5 shows the dollar value of delay components (delay from cars and trucks and from potential secondary incidents) for each VDOT district. For example, the first row in Table 5(a) shows details for the Bristol District, where the dollar values for congestion costs resulting from cars and trucks are $60.09 and $10.73 per incident-minute, respectively. The total delay cost per incident-minute when both primary and secondary incidents is considered is $71.47 per incident-minute.

As shown in Table 5(a), during AM peak periods (6 AM to 10 AM), the relatively urban districts (Northern Virginia, Fredericksburg, Hampton Roads, and Richmond) have higher per-incident-minute costs for lane-blocking incidents. The highest per-incident-minute cost ($1,347.01) was in the Northern Virginia District.

When Table 5(a) and 5(b) are compared, the per-incident-minute costs for non-blocking incidents are significantly lower than that for the lane-blocking counterparts. The congestion costs for the relatively rural districts can be lower than $1 per incident-minute.

Table 5. Incident Congestion Cost per Incident-Minute During AM Peak Hours (6 AM to 10 AM) by VDOT District for (a) Lane-Blocking Incidents, and (b) Non-Blocking Incidents

(a)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	60.09	10.73	0.53	0.12	71.47
Culpeper	157.44	14.46	2.09	0.23	174.21
Fredericksburg	675.09	95.76	15.95	2.44	789.24
Hampton Roads	536.41	69.68	14.85	2.06	622.99
Northern Virginia	1,150.13	120.33	67.39	9.16	1,347.01
Richmond	341.36	44.80	8.27	1.18	395.62
Salem	130.32	15.98	1.85	0.23	148.39
Staunton	105.89	11.10	1.20	0.13	118.32
Average	**382.76**	**46.53**	**15.79**	**2.18**	**447.26**

(b)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	0.17	0.03	0.30	0.06	0.55
Culpeper	1.34	0.12	0.69	0.06	2.21
Fredericksburg	7.76	0.96	4.07	0.58	13.36
Hampton Roads	9.73	1.68	4.88	0.75	17.04
Northern Virginia	116.85	18.43	28.80	4.16	168.25
Richmond	3.23	0.87	2.55	0.41	7.06
Salem	0.78	0.07	0.73	0.08	1.67
Staunton	0.56	0.05	0.45	0.05	1.10
Average	**20.07**	**3.26**	**6.08**	**0.89**	**30.30**

The last row in each sub-table in Table 5 shows the statewide average values. As shown in Table 5, the statewide average delay costs during the AM peak hours are $447.26 and $30.30 per incident-minute for lane-blocking incidents and non-blocking incidents, respectively.

Table 6 is the equivalent of Table 5 in showing the incident congestion cost per incident-minute during PM peak hours. Comparing Tables 5 and 6, the statewide average value for lane-blocking incidents during PM peak hours increased from $447.26 to $528.71 per incident-minute whereas that for non-blocking incidents decreased from $30.30 to $22.32 per incident-minute. From the district perspective, the delay cost per incident-minute during PM peak hours is more evenly distributed compared to AM peak hours. The main suspected reason for this is the difference between traffic demand patterns during AM and PM peak hours; to be more specific, major traffic congestion can occur on different links (with different numbers of lanes) during different hours of the day.

Table 6. Incident Congestion Cost per Incident-Minute During PM Peak Hours (3 PM to 7 PM) by VDOT District for (a) Lane-Blocking Incidents, and (b) Non-Blocking Incidents

(a)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	102.93	19.57	1.22	0.27	123.99
Culpeper	232.13	18.20	3.92	0.33	254.57
Fredericksburg	743.54	130.60	18.01	3.71	895.86
Hampton Roads	690.82	95.63	23.53	3.49	813.47
Northern Virginia	1,086.79	98.30	37.98	4.19	1,227.27
Richmond	440.04	54.90	12.03	1.62	508.60
Salem	204.19	26.87	3.56	0.48	235.10
Staunton	190.38	21.10	3.20	0.37	215.05
Average	**456.22**	**55.63**	**14.90**	**1.98**	**528.71**

(b)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	0.47	0.07	0.53	0.10	1.18
Culpeper	2.72	0.15	1.06	0.08	4.01
Fredericksburg	8.82	1.16	4.75	0.92	15.65
Hampton Roads	31.64	5.07	9.12	1.39	47.21
Northern Virginia	34.29	6.25	13.49	1.73	55.76
Richmond	6.22	0.90	3.71	0.54	11.36
Salem	1.77	0.18	1.13	0.14	3.22
Staunton	1.61	0.14	0.85	0.09	2.69
Average	**14.07**	**2.30**	**5.22**	**0.74**	**23.32**

Table 7, equivalent to Tables 5 and 6, shows the incident congestion cost per incident-minute on weekends. Although the statewide average values during weekends were lower than the peak hour counterparts, there were variations in costs at the district level. Comparing Tables 5(a), 6(a), and 7(a), the Fredericksburg District had the highest delay cost per incident-minute during weekends and the Northern Virginia District had the highest cost per incident-minute during weekday peak hours. This observation resembled the actual traffic congestion pattern in the Fredericksburg District with high levels of interstate congestion during weekends.

Table 7. Incident Congestion Cost per Incident-Minute During Weekends (8 AM to 5 PM) by VDOT District for (a) Lane-Blocking Incidents, and (b) Non-Blocking Incidents

(a)

District	Congestion Cost ($ per incident-minute) Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	100.28	17.74	1.12	0.23	119.36
Culpeper	173.08	13.09	2.28	0.19	188.65
Fredericksburg	1,011.02	157.01	28.99	4.86	1,201.88
Hampton Roads	342.44	45.87	7.98	1.12	397.42
Northern Virginia	971.47	94.94	37.86	4.48	1,108.75
Richmond	294.54	31.30	6.74	0.72	333.31
Salem	169.03	23.39	2.74	0.42	195.59
Staunton	178.97	19.97	3.11	0.37	202.42
Average	**330.29**	**38.69**	**10.38**	**1.30**	**380.66**

(b)

District	Congestion Cost ($ per incident-minute) Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	0.45	0.07	0.51	0.09	1.12
Culpeper	1.42	0.09	0.75	0.06	2.31
Fredericksburg	13.67	1.52	6.27	0.98	22.45
Hampton Roads	2.55	0.32	2.22	0.32	5.42
Northern Virginia	33.78	5.24	13.27	1.72	54.01
Richmond	2.62	0.23	2.02	0.22	5.09
Salem	1.34	0.14	0.87	0.11	2.47
Staunton	1.45	0.13	0.79	0.09	2.46
Average	**6.79**	**0.96**	**3.29**	**0.43**	**11.46**

Incident Congestion Cost With Different Closure Types and Detour Volume

The number of lanes closed due to incidents has profound impacts on capacity. Table 8 shows the delay cost per incident-minute for closure types ranging from one lane closed, two lanes closed, to three or more lanes closed. Comparing Tables 5(b), 8(a), 8(b), and 8(c), the statewide average per-incident-minute cost values increased with the number of lanes closed as follows:

- *From shoulder-closure only to one-lane closure:* a $137.80 increase (from $30.30 to $168.10)
- *From one-lane to two-lane closure:* a $967.10 increase (from $168.10 to $1135.20)
- *From two-lane to three-lane closure:* a $1,939.68 increase (from $1,135.20 to $3,074.88).

As expected, the per-incident-minute cost increased significantly with the number of closed lanes. From the district level perspective, such cost increases were more substantial for the relatively urban districts having higher traffic volumes (e.g., Northern Virginia, Fredericksburg, and Hampton Roads).

Table 8. Congestion Cost per Incident-Minute During AM Peak Hours (6 AM to 10 AM) by VDOT District for (a) One-Lane Closure, (b) Two-Lane Closure, and (c) Three-Lane Closure Incidents

(a)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	2.76	0.69	0.36	0.09	3.90
Culpeper	38.30	4.38	1.18	0.21	44.70
Fredericksburg	123.85	18.21	13.32	2.11	157.49
Hampton Roads	212.00	29.27	13.38	1.88	256.53
Northern Virginia	424.84	55.10	59.57	8.25	547.76
Richmond	77.95	12.73	6.77	0.99	98.44
Salem	22.30	2.96	1.48	0.20	26.94
Staunton	12.75	1.37	0.98	0.11	15.22
Average	**134.04**	**18.39**	**13.75**	**1.92**	**168.10**

(b)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	276.85	48.38	1.20	0.22	326.66
Culpeper	643.68	55.63	3.20	0.31	702.81
Fredericksburg	1,252.48	180.09	21.10	3.08	1,456.75
Hampton Roads	1,345.80	171.24	19.13	2.61	1,538.78
Northern Virginia	2,081.80	208.90	83.64	11.13	2,385.48
Richmond	861.25	106.89	11.50	1.58	981.20
Salem	519.19	65.10	3.20	0.36	587.86
Staunton	486.02	50.80	2.10	0.22	539.14
Average	**995.28**	**117.02**	**20.19**	**2.71**	**1,135.20**

(c)

District	Congestion Cost ($ per incident-minute)				
	Car	Truck	Secondary Incident Car	Secondary Incident Truck	Total Cost
Bristol	614.46	117.07	1.73	0.35	733.61
Fredericksburg	2,829.13	394.81	23.12	3.33	3,250.38
Hampton Roads	2,374.30	294.99	20.83	2.70	2,692.81
Northern Virginia	3,945.22	365.55	88.45	11.47	4,410.69
Richmond	2,385.36	298.09	18.99	2.64	2,705.08
Salem	1,202.17	98.89	5.39	0.40	1,306.86
Average	**2,726.42**	**304.82**	**38.54**	**5.06**	**3,074.88**

Only interstate main lanes were counted in the study; the auxiliary lanes and truck climbing lanes were not included in the analysis.

Similar to the reduced capacity due to incidents, traffic demands were also highly related to the congestion delays and costs. Detour operation is a common practice, diverting traffic demands onto an alternative route, aimed at mitigating congestion caused by incidents. Table 9 shows the delay cost per incident-minute, under different assumed detour volume proportions, for closure types ranging from one lane closed, two lanes closed, to three or more lanes closed.

Each row in each sub-table in Table 9 compares the delay cost per incident-minute assuming (1) 0%, (2) 10%, and (3) 20% of the incoming traffic taking the detour route during an incident. Impacts and delay increase on the detour route were not considered in this study.

Table 9. Comparison of Congestion Costs per Incident-Minute During AM Peak Hours (6 AM to 10 AM) Under Different Detour Volumes by VDOT District for (a) One-Lane Closure, (b) Two-Lane Closure, and (c) Three-Lane Closure Incidents

(a)

District	Congestion Cost ($ per incident-minute)		
	Total	**Total Cost – Detour 10%**	**Total Cost – Detour 20%**
Bristol	3.90	2.75	2.30
Culpeper	44.70	31.47	41.22
Fredericksburg	157.49	96.48	102.63
Hampton Roads	256.53	143.97	89.84
Northern Virginia	547.76	195.01	103.71
Richmond	98.44	57.84	45.53
Salem	26.94	18.90	16.71
Staunton	15.22	14.42	21.28
Average	**168.10**	**80.54**	**54.13**

(b)

District	Congestion Cost ($ per incident-minute)		
	Total	**Total Cost – Detour 10%**	**Total Cost – Detour 20%**
Bristol	326.66	282.03	242.17
Culpeper	702.81	598.32	505.00
Fredericksburg	1,456.75	1,086.06	797.62
Hampton Roads	1.538.78	1,131.18	840.85
Northern Virginia	2.385.48	1,430.80	981.93
Richmond	981.20	750.73	573.59
Salem	587.86	493.01	420.74
Staunton	539.14	462.62	393.27
Average	**1,135.20**	**818.35**	**617.99**

(c)

District	Congestion Cost ($ per incident-minute)		
	Total	**Total Cost – Detour 10%**	**Total Cost – Detour 20%**
Bristol	733.61	641.07	553.85
Fredericksburg	3,250.38	2,588.25	2,067.57
Hampton Roads	2,692.81	2,109.87	1,642.27
Northern Virginia	4,410.69	2,984.48	2,161.45
Richmond	2.705.08	2,163.81	1,724.09
Salem	1,306.86	1,114.05	940.92
Average	**3,074.88**	**2,294.02**	**1,758.61**

Comparing Table 9(a), 9(b), and 9(c), the reduction in congestion cost with a 20% detour rate increased from $113.97 per incident-minute (for one-lane closure incidents, reduced from $168.10 to $54.13); $517.21 per incident-minute (for two-lane closure incidents, reduced from $1,135.20 to $617.99); to $1,316.27 per incident-minute (for three-lane closure incidents, reduced from $3,074.88 to $1,758.61). As expected, the benefit derived from detour operation became more significant as the number of closed lanes increased.

Incident Congestion Cost Aggregated at the Corridor Level

Given that traffic demands often have clear directional patterns by different times-of-day, the incident congestion costs were aggregated at the corridor level to provide more representative cost values for potential use cases. Table 10 shows the top 15 corridors with the highest delay costs per incident-minute during (a) AM peak hours, and (b) PM peak hours.

I-395 is one of the most high-traffic corridors in Virginia, serving as main regional commuting routes between Virginia and Washington, D.C. As seen in Table 10(a), during the AM peak hours, the "Northern Virginia I-395N" corridor (inbound to D.C.) had a delay cost of $1,220.68 per incident-minute, which was higher than the delay cost ($606.60 per incident-minute) for the "Northern Virginia I-395S" corridor (outbound from D.C.). In contrast, in Table 10(b), the "Northern Virginia I-395S" corridor had a cost ($2,120.88 per incident-minute) higher than that for the "Northern Virginia I-395N" corridor ($964.16 per incident-minute) during the PM peak.

Table 10. Comparison of Congestion Costs per Incident-Minute for Top 15 Corridors With Highest Delay Costs During (a) AM Peak, and (b) PM Peak

(a)

District	Route Direction	Congestion Cost ($ per incident-minute)		
		Car	Truck	Total
Northern Virginia	I-95N	3,960.00	525.93	4,901.02
Northern Virginia	I-395N	1,124.18	59.12	1,220.68
Northern Virginia	I-95S	1,020.79	82.75	1,134.24
Hampton Roads	I-644N	838.63	79.68	944.18
Fredericksburg	I-95N	816.08	91.74	931.83
Hampton Roads	I-64E	762.28	105.43	892.77
Northern Virginia	I-495S	834.41	29.03	885.37
Hampton Roads	I-264E	619.53	102.50	740.11
Hampton Roads	I-64W	632.68	76.60	728.34
Richmond	I-95N	578.44	67.55	663.39
Hampton Roads	I-264W	540.61	83.85	644.90
Fredericksburg	I-95S	518.44	100.24	630.81
Northern Virginia	I-495N	557.50	40.97	611.13
Northern Virginia	I-395S	508.63	85.40	606.60
Richmond	I-95S	514.34	52.97	580.14

(b)

District	Route Direction	Congestion Cost ($ per incident-minute)		
		Car	Truck	Total
Northern Virginia	I-395S	1,699.53	312.11	2,120.88
Northern Virginia	I-95N	1,647.71	180.47	1,899.62
Northern Virginia	I-95S	1,637.22	129.01	1,829.94
Hampton Roads	I-464S	1,277.17	379.87	1,726.83
Hampton Roads	I-664S	1,338.79	127.20	1,539.83
Northern Virginia	I-495S	1,330.90	45.97	1,422.35
Fredericksburg	I-95S	937.13	214.30	1,183.37
Hampton Roads	I-264W	948.61	142.25	1,127.07
Hampton Roads	I-264E	812.67	145.62	996.17
Northern Virginia	I-395N	892.35	45.66	964.16
Richmond	I-95S	722.00	88.81	834.08
Hampton Roads	I-64E	702.87	72.75	796.82
Hampton Roads	I-64W	659.70	99.88	779.26
Richmond	I-195S	487.60	250.06	749.69
Northern Virginia	I-495N	680.92	50.07	748.03

This could suggest that some corridors have clear delay cost differences by time-of-day due to their directional traffic patterns. The selection of cost per incident-minute should be carefully considered when projects across different locations or covering different periods are compared or evaluated.

Given that a long interstate (e.g., I-95 or I-81) often traverses both urban and rural areas, its congestion cost per incident-minute could change over those areas. Table 11 shows a comparison of congestion cost per incident-minute on I-95N across different districts during AM peak hours. There were significant differences in congestion costs for different districts, ranging from $71.99 to $4,901.02 per incident-minute; a single average per-incident-minute value of $1,591.08 is not representative of any of those costs.

The congestion costs by time-of-day for all studied corridors are provided in Tables A1 and A2 in the Appendix for lane-blocking and non-blocking incidents, respectively.

Table 11. Comparison of Congestion Costs per Incident-Minute on I-95N Across Multiple Districts During AM Peak

		Congestion Cost ($ per incident-minute)		
District	**Route Direction**	**Car**	**Truck**	**Total**
Northern Virginia	I-95N	3,960.00	525.93	4,901.02
Fredericksburg	I-95N	816.08	91.74	931.83
Richmond	I-95N	578.44	67.55	663.39
Hampton Roads	I-95N	62.86	8.67	71.99
Average		**1,309.55**	**168.44**	**1,591.08**

Incident Congestion Cost With Interstate Full Roadway Closure

Table 12 shows the comparison of congestion cost per incident-minute on I-66E and I-95N (the major commuting directions) during AM peak hours in the Northern Virginia District when all lanes are closed. Although the congestion cost per incident-minute generally increases with traffic volume, some exceptions can be expected when links have similar traffic volumes but different numbers of lanes. From Table 12, the two-lane section on I-66 had an average traffic volume of 2,383.16 vehicles per hour; that on the three-lane section was 2,582.05 vehicles per hour. When a link is fully closed, the queue will increase at the rate of arriving vehicles; one can therefore expect similar queue lengths on the two-lane and three-lane sections after the same lane-closure duration. However, the queue discharge rates for two-lane and three-lane sections will be significantly different, and thus the traffic queues on three-lane sections are expected to clear sooner and to have lower delay than on two-lane sections.

Table 12. Comparison of Congestion Costs per Incident-Minute for Full-Roadway-Closure Incidents on I-66E and I-95N in the Northern Virginia District During AM Peak Hours

District	Route Direction	No. of Lanes	No. of Closed Lanes	Average Traffic Volume (vph)	Total Congestion Cost ($ per incident-minute)
Northern Virginia	I-95N	3	3	4,481.41	6,074.49
Northern Virginia	I-95N	4	4	6,776.77	19,496.54
Northern Virginia	I-66E	2	2	2,383.16	2,304.52
Northern Virginia	I-66E	3	3	2,582.05	2,202.39
Northern Virginia	I-66E	4	4	4,449.62	4,251.16
Average				**4,571.34**	**4,815.76**

Discussion

Caveats and Limitations

Since the objective of this study was to develop planning-level cost estimates, there are several assumptions and limitations that should be understood before these values are applied.

- The reduction of incident clearance time and delay is one of the primary benefits of incident management programs. This study converted the changes in travel time due to traffic incidents to dollar values. The hourly costs considered in the study included both the driver/passenger value of time and the vehicle operating costs (e.g., fuel, vehicle depreciation, maintenance). Safety costs were not considered in this study.

- The model for predicting secondary incident probability (Goodall, 2017) was originally developed using I-66 data and was not validated for other interstate routes. The cost of secondary incidents was estimated by multiplying the probability of a secondary incident by the aggregated congestion cost of primary incidents. This approach is deemed appropriate for planning-level estimates as the cost due to secondary incidents was found to account for less than 5% of the total per-incident-minute congestion cost.

- The number of lanes for a link was defined as the number of freeway main lanes. Auxiliary lanes and truck climbing lanes were not included. Truck climbing lanes are available for a limited number of links, mostly on I-81 in the Bristol and Salem districts. The average incident cost per incident-minute for those links could be overestimated but it was assumed that it would not significantly affect the aggregated value at the corridor level.

- The proposed queue estimation method (which assumes that all lanes are open after an incident is cleared) is a simplification, as the incident response team often moves vehicles involved in a lane-blocking incident to the shoulder and opens up the lanes to traffic before the incident is fully cleared.

- The congestion cost per incident-minute under detour operations was estimated by reducing the number of arriving vehicles on a link. This study focused on the congestion costs on interstates and did not extend to the impact on the network of arterial roads that provide access to and from the interstates.

CONCLUSIONS

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

- *When applied to valid data, the proposed methodology produces reasonable planning-level incident congestion cost estimates.* The average per-minute incident congestion costs on Virginia interstates under different spatial aggregations (i.e., state, district, and district-route levels); temporal aggregations (e.g., AM peak, mid-day, PM peak, and weekend periods); and closure types (e.g., shoulder-closed, single-lane, and multiple-lane closure situations) are comparable to the values in the literature. The technical review panel also validated that congestion costs appeared to be reasonable and intuitive.

- *The congestion cost per incident-minute increases as the number of closed lanes increases.* The average per-incident-minute cost increases are more substantial for the more urban districts that have higher traffic volumes.

- *The per-incident-minute congestion cost generally increases as the traffic demand increases for full-roadway-closure incidents.* Some exceptions were observed among links having different numbers of lanes but with similar traffic demands.

- *The per-incident-minute congestion cost varies across Virginia districts, routes, time-of-day, and day-of-week; the appropriate corridor cost values should be used to compare or evaluate projects across different locations or different time periods.* As expected, incident congestion costs per incident-minute vary with respect to traffic demand and roadway geometry. Given that a long interstate (e.g., I-95) often traverses both urban and rural areas, the congestion cost per incident-minute varies across districts. Appropriate values that best represent local conditions should be selected.

RECOMMENDATIONS

1. *VDOT's Operations Division (OD) should use the per-incident-minute congestion cost and the value of time developed in this study for their cost-effectiveness analyses.* Given that incident congestion costs vary with respect to time-of-day, day-of-week, and route, the OD

should select spatial-temporal aggregation suitable for their analyses. Moreover, the value of time by vehicle type should be used where applicable to ensure consistency across comparisons. The OD should also work to include these values in commonly used analysis tools.

2. *VDOT's OD should develop a plan to maintain and update the per-incident-minute congestion cost values. This maintenance and update plan should include updating the cost values under different spatial and temporal aggregations, the internal cost value update interval, and the criteria for revising the publicized cost values.* Delay and cost variables (e.g., traffic volume, hourly wage, truck operation cost) vary over time, and the latest values are recommended to produce up-to-date congestion costs per incident-minute. The maintenance and update plan should include the considerations for cost value update intervals, data sources, and standard rounding procedures.

3. *VDOT's OD should develop a field-ready application (app) for easy use by staff with various technical levels to access quickly the per-incident-minute congestion cost values.* This will provide a field ready tool for VDOT staff and first responders to assess the costs of incidents while on-site. This app should require minimal user training, easy access from mobile devices, and easy information sharing within VDOT and with its partners (e.g., Virginia State Police).

4. *The Virginia Transportation Research Council (VTRC) should pursue additional research to expand the method proposed in this study for estimating incident congestion cost on non-interstate limited access facilities in Virginia.*

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, within 3 months of the publication of this report, VDOT's OD will start using the developed incident congestion cost values in their cost-effectiveness analyses. Within 6 months of the publication of this report, the OD will meet with the University of Maryland CATT lab to discuss updating RITIS to include Virginia-specific value-of-time values in the RITIS User Delay Cost Analysis program.

With regard to Recommendation 2, within 6 months of the publication of this report, VDOT's OD will initiate the development of a plan to maintain and update the per-incident-minute congestion cost values. VTRC will provide technical assistance as needed.

With regard to Recommendation 3, within 12 months of the publication of this report, VDOT's OD will start a project to develop a field-ready app to grant easy access to the cost values for the field personnel.

With regard to Recommendation 4, within 6 months of the publication of this report, VDOT's OD will work with VTRC to initiate a technical assistance project to estimate incident congestion costs on Virginia limited access facilities beyond interstates.

Benefits

In the past, VDOT used a per-minute delay cost adopted from a 2016 Washington State DOT publication (Washington State DOT, 2016) to estimate congestion cost due to traffic incidents. The benefits of implementing the recommendations will be the consistent and quick planning-level estimates of incident congestion costs with improved accuracy.

The implementation of Recommendation 1 will improve the accuracy, consistency, and interpretability of results for the cost-effectiveness analyses. Updating the User Delay Cost Analysis tool in RITIS will further increase the consistency of analysis results by updating a commonly used analysis tool.

The implementation of Recommendation 2 will provide up-to-date congestion cost estimates that are customized to Virginia conditions and thus help to meet VDOT's business needs better.

The implementation of Recommendation 3 will provide an easy-to-use tool for VDOT staff to look up congestion cost values quickly and to facilitate communication with stakeholders, such as first responders at the scene of an incident.

The implementation of Recommendation 4 will provide a method and a set of incident congestion cost values that could be applied to all limited access highways in Virginia.

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APPENDIX
INCIDENT CONGESTION COST BY LANE-CLOSURE TYPE

Table A1. Lane-Blocking Incident Congestion Cost

District	Route/Direction	Congestion Cost ($ per incident-minute)			
		AM Peak	**Mid-Day**	**PM Peak**	**Weekend**
Bristol	I-77N	51.25	88.22	77.10	112.93
	I-77S	49.95	89.44	87.11	112.70
	I-81N	73.44	114.87	114.72	138.32
	I-81S	83.58	142.44	160.36	151.05
Culpeper	I-64E	171.66	156.03	290.72	207.33
	I-64W	237.82	167.70	246.38	206.01
	I-66E	172.59	99.38	99.54	208.72
	I-66W	73.81	168.57	337.15	220.97
Fredericksburg	I-95N	931.83	713.21	637.10	1174.16
	I-95S	630.81	1193.15	1183.37	1466.35
Hampton Roads	I-264E	740.11	611.00	996.17	438.20
	I-264W	644.90	660.22	1127.07	372.02
	I-464N	400.95	102.95	132.36	82.91
	I-464S	160.63	471.94	1726.83	143.80
	I-564E	161.41	153.95	145.65	129.87
	I-564W	206.79	152.54	160.06	145.44
	I-64E	892.77	810.27	796.82	665.45
	I-64W	728.34	569.27	779.26	687.11
	I-664N	944.18	384.29	665.34	369.02
	I-664S	415.39	921.46	1539.83	369.17
	I-95N	71.99	114.62	107.73	221.96
	I-95S	75.97	121.33	106.12	186.69
Northern Virginia	I-395N	1220.68	694.77	964.16	1261.93
	I-395S	606.60	1772.67	2120.88	1465.40
	I-495N	611.13	674.12	748.03	663.91
	I-495S	885.37	1167.81	1422.35	870.74
	I-66E	574.62	549.54	655.01	694.83
	I-66W	378.06	528.90	598.21	528.80
	I-95N	4901.02	3038.52	1899.62	3355.35
	I-95S	1134.24	1319.01	1829.94	1433.44
Richmond	I-195N	356.92	125.90	263.49	108.51
	I-195S	367.49	228.98	749.69	158.47
	I-295N	323.83	147.13	264.02	205.57
	I-295S	159.04	129.57	392.61	144.40
	I-64E	503.68	347.50	627.46	418.79
	I-64W	454.20	319.10	558.50	354.65
	I-85N	96.29	85.83	90.29	118.22
	I-85S	54.10	88.20	124.33	100.92
	I-95N	663.39	608.90	741.27	744.85
	I-95S	580.14	598.51	834.08	563.39
Salem	I-581N	276.90	264.45	400.98	201.26
	I-581S	403.17	293.23	434.99	246.17
	I-77N	74.86	136.74	104.33	204.39
	I-77S	60.95	122.01	120.07	169.31
	I-81N	174.94	240.18	267.01	307.84
	I-81S	136.31	193.30	251.56	209.73
Staunton	I-64E	49.79	54.76	59.34	70.50
	I-64W	42.39	59.82	81.64	66.68
	I-66E	81.43	83.34	91.41	144.44
	I-66W	70.32	111.73	146.01	146.22
	I-81N	148.34	229.33	283.21	339.36
	I-81S	159.34	242.84	290.20	283.76

Table A2. Non-Blocking Incident Congestion Cost

District	Route/Direction	Congestion Cost ($ per incident-minute)			
		AM Peak	Mid-Day	PM Peak	Weekend
Bristol	I-77N	0.40	0.92	0.77	1.43
	I-77S	0.31	0.75	0.78	1.07
	I-81N	0.59	1.07	1.13	1.36
	I-81S	0.62	1.20	1.46	1.30
Culpeper	I-64E	2.34	1.62	4.32	2.58
	I-64W	3.18	1.89	3.85	2.57
	I-66E	2.00	0.80	0.85	2.47
	I-66W	0.54	2.04	6.40	3.06
Fredericksburg	I-95N	18.15	12.15	11.28	25.02
	I-95S	8.03	17.81	20.51	26.48
Hampton Roads	I-264E	8.84	6.05	48.06	4.61
	I-264W	23.90	6.87	37.75	4.34
	I-464N	4.58	0.81	1.12	0.64
	I-464S	1.11	3.09	177.20	0.97
	I-564E	1.44	1.35	1.38	1.09
	I-564W	2.36	1.42	1.59	1.37
	I-64E	28.49	55.19	30.29	11.50
	I-64W	16.66	6.89	12.45	9.31
	I-664N	37.76	3.61	8.69	3.67
	I-664S	4.99	131.68	262.02	3.99
	I-95N	0.46	0.97	0.94	2.57
	I-95S	0.52	1.09	0.96	2.07
Northern Virginia	I-395N	28.60	7.76	12.63	19.58
	I-395S	7.51	178.50	307.45	37.49
	I-495N	8.19	8.36	10.45	8.47
	I-495S	12.29	18.81	37.77	11.50
	I-66E	8.55	7.35	9.42	10.03
	I-66W	5.30	7.42	12.07	8.09
	I-95N	1077.28	333.81	89.60	411.97
	I-95S	18.20	20.63	52.44	26.99
Richmond	I-195N	5.55	1.48	3.71	1.32
	I-195S	3.49	1.81	7.66	1.29
	I-295N	4.72	1.38	3.18	2.16
	I-295S	1.79	1.25	8.54	1.52
	I-64E	17.60	4.47	11.36	6.86
	I-64W	8.30	4.30	10.24	6.28
	I-85N	0.85	0.69	0.77	1.09
	I-85S	0.36	0.71	1.25	0.88
	I-95N	9.17	8.66	19.38	12.51
	I-95S	7.25	6.82	19.39	7.47
Salem	I-581N	2.03	1.80	3.36	1.32
	I-581S	3.73	2.25	4.22	1.85
	I-77N	0.65	1.61	1.16	2.73
	I-77S	0.54	1.59	1.65	2.57
	I-81N	1.84	2.81	3.57	4.05
	I-81S	1.43	2.21	3.44	2.51
Staunton	I-64E	0.41	0.41	0.52	0.60
	I-64W	0.28	0.45	0.77	0.52
	I-66E	0.82	0.83	1.03	2.12
	I-66W	0.61	1.34	2.25	1.95
	I-81N	1.42	2.57	3.63	4.54
	I-81S	1.52	2.78	3.75	3.52