DEVELOPMENT OF RATE-BASED STATEWIDE SAFETY PERFORMANCE MEASURES OF WORK ZONES USING IMPERFECT EXPOSURE DATA: A VIRGINIA CASE STUDY

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ABSTRACT

Ideally, state departments of transportation would track work zone crashes over time while simultaneously accounting for traffic exposure using work zone vehicle miles of travel (VMT). Work zone VMT is often difficult to obtain, however, because of inconsistent logging of work zone locations and changes in traffic volumes during construction. As a result, the Virginia Department of Transportation was interested in developing reliable work zone safety performance measures that could account for exposure using data that were readily available to them from existing sources. This study developed statewide rate-based measures for Virginia by combining two data sources: the crash database and the VaTraffic database containing information on roadway activities such as work zones. Data from 2009-2013 were prepared for interstate and non-interstate highways at four temporal levels. A linearity condition, with the numerator and denominator of a rate being proportional, was used to develop recommended work zone safety performance measures.

The analysis revealed several reliable rate-based measures that did not rely on having accurate work zone VMT. Rates based on the exposure reflecting all three output-aspects of work zones (count, duration, and length) were better than those reflecting two of the three. It is worth noting that the study conclusions are valid for statewide annual safety performance measures and may not be valid for measures at different geographical and/or temporal levels. Although better results could likely be achieved if reliable work zone VMT were available, the developed measures appear to represent an improvement over pure crash count measures.

Keywords: Work Zone Safety, Performance Measures, Crash Exposure
INTRODUCTION

According to the Code of Federal Regulations (23 CFR Part 630, Subpart J) relevant to traffic safety and mobility in work zones, “[s]tates shall continually pursue improvement of work zone safety and mobility by analyzing work zone crash and operational data from multiple projects to improve State processes and procedures . . . [and] should maintain elements of the data and information resources that are necessary to support these activities.” Using performance measures is a way of satisfying this requirement (1). By establishing appropriate performance measures, work zone impacts can be assessed, monitored, and compared over time.

The Virginia Department of Transportation (VDOT) has been using the annual numbers of persons killed and seriously injured in work zone traffic crashes as the only statewide work zone safety performance measures for federal reporting purposes. The numbers of fatalities and serious injuries are important safety metrics that directly measure the consequences of traffic crashes at work zones. However, several assumptions are required for these numbers to serve as reliable performance measures. Direct comparisons of crash frequencies over multiple years assume that the exposure (e.g., number, duration, length, and vehicle miles of travel [VMT] of work zones) is similar from year to year. Although crash frequencies are easy to obtain and understand, they do not reflect information on the number, duration, traffic exposure, or spatial extent of work zones. The number of work zone crashes might fluctuate simply because of changes in exposure, rather than any underlying change in crash likelihood.

Given the federal emphasis on work zone safety performance measures and increasing use of data-driven approaches, there was a need to develop and refine further the performance measures used by VDOT. Although it would have been ideal to develop new rate-based measures based on work zone VMT, there were known limitations in existing systems related to the logging of work zones and measurements of traffic during construction and maintenance activities. Existing data sources needed to be reviewed to determine which measures could be consistently and reliably calculated to account better for crash frequency and exposure. Improved performance measures would allow for better tracking of work zone safety impacts and help identify areas where additional attention might be needed to improve safety.

The purpose of this study was to develop improved work zone safety performance measures for Virginia using available data sources; the focus was on statewide safety performance measures of work zones. Incidents not found on police crash reports, such as workers’ injuries resulting from a crash but not reported to the police, were not included. For the study, 5 years (2009-2013) of data were collected from four sources containing crash data, roadway inventory data, traffic volume data, and roadway activities (e.g., work zone and special event) data.

LITERATURE REVIEW

Types of Performance Measures

There are three common types of metrics related to traffic safety: (1) count measures, (2) exposure measures, and (3) rate measures. Count measures are intended to measure directly traffic crash consequences (e.g., the numbers of fatalities and crashes), and exposure measures are intended to capture the level of crash exposure to the traveling public (e.g., traffic volume and VMT). There are two types of exposure measures: output-based measures quantifying efforts or resources being expended (e.g., number of hours for lane closures due to work zone
activities), and outcome-based measures quantifying the level of work zone crash risk exposed to the traveling public (e.g., work zone VMT) (1).

Rate measures combine the count and exposure measures into a single value, typically by dividing a count by an exposure (e.g., fatalities per million VMT), normalizing varying levels of an exposure. Since rate measures reflect both count and exposure, they are more appropriate for evaluating and comparing safety performance across areas and/or over time. Studies have found that statewide evaluation of safety policies and procedures are best accomplished using rate measures (1). Count and rate measures can be classified as “safety measures”; exposure measures are in their own category (1).

**Strategic Highway Safety Plans**

The strategic highway safety plans (SHSPs) of 30 states were surveyed to identify work zone safety performance measures used in practice (see Kweon et al. [2] for the full list of the states). Nineteen of the plans reviewed included work zone safety in their focus areas. Of these, 6 addressed it as a secondary or additional emphasis area. It should be noted that the states developed their initial SHSPs in 2006, and many of them have revised their plans since then. As a result, it is possible that work zone safety could have been included in the initial plan and dropped in later years (e.g., Maryland’s SHSP [3] and Virginia’s SHSP [4]).

Several states established goals for work zone safety, but the performance measures used to quantify the goals varied. For example, California used traffic fatality count at construction and maintenance work zones (5), Pennsylvania used traffic fatality and major injury count at all work zones (6), and New York used fatal and injury traffic crash count at construction work zones (7). Although goals for work zone safety were not stated, other states used various metrics in measuring and discussing work zone safety. For example, Indiana used fatality and incapacitating injury counts at work zone crashes (8), Ohio used rear-end crash counts caused by work zones (9), and Missouri used fatality and serious injury counts and fatal and serious injury crash counts at work zone crashes (10). Some states such as Massachusetts (11) and Texas (12) specifically noted workers injured from traffic crashes being included in their metrics. Although metrics not directly measuring traffic safety of work zones were also used (e.g., number of speeding tickets issued at work zones, number of work zones inspected, and percent of inspected work zone traffic elements), the majority of work zone safety performance measures were counts of traffic crashes and/or crash victims at work zones. The count measures have the advantage of being easy to determine but fail to account for changes in work zone crash exposure. Lack of exposure data represents a serious limitation in using work zone count data as the performance measure. There is a need to account better for changes in exposure using data that may be readily available to an agency.

**DATA**

This study attempted to integrate data from four VDOT sources: (1) a crash database containing police crash reports; (2) the VaTraffic database containing information on incidents, work zones, weather conditions, and so on; (3) a roadway inventory database containing road use and geometric characteristics such as functional classification; and (4) the Traffic Monitoring System (TMS) database containing traffic characteristics such as annual average daily traffic volume (AADT). Before discussing the methods used to develop safety performance measures, the characteristics of each data set and their integration for analysis are reviewed.
Work Zone Crash Dataset
Work zone crash data, which included information on the crash, vehicle, and persons involved in the crash, were first merged with the roadway inventory database that contained information on roadway characteristics at the site. The resulting dataset, the work zone crash dataset, contained road characteristics of crash sites and crash characteristics. The merging process was performed using structured query language (SQL) codes executing algorithms mapping the crash database to the roadway inventory database based on a linear referencing system.

It should be noted that although several decades of police crash reports are available in the crash database, explicit work zone information was not included in the records until 2003. Since 2003, the crash report form has contained two pieces of information related to a work zone: work zone status and worker’s presence. The work zone status information was used to identify work zone crashes.

Work Zone Activity Dataset
The VaTraffic database stores daily reported roadway activities in three tables (event master, planned event, and event location tables). Standardized formats, terms, and definitions established by VDOT regional traffic operations managers are used for maintaining these tables. The event master table contains high-level information on an event such as the event ID, event type (e.g., incident, special event, and work zone), and start/cleared date and time. The planned event table contains information on planned events such as detour routes and speed limits. The event location table contains detailed information on time/sequence of events such as road segment of an event, segment type, level of congestion severity, and delay type.

Events with the event type of “work zone” were extracted from the event master table and then joined with the planned event and event location tables to append characteristics of the work zone events, resulting in the work zone activity dataset. The event ID was utilized as a primary key for joining the tables and customized SQL codes were developed to execute the joining. An individual work zone is defined as a work zone event with a unique event ID.

Data Issues
Several difficulties and data challenges were encountered while joining the crash, roadway inventory, traffic, and work zone information. Major issues and their resolution are discussed here.

Defining a Work Zone
As described previously, this study defined a work zone as an event with an event type of “work zone” in the VaTraffic database. Work zone events with the same event ID were combined and considered to have occurred within a single work zone. Thus, a single work zone project might have been coded as multiple events if there were multiple lane closure events or changes in phasing. While validating work zone events, it was found that there were variations in how event IDs were created and assigned for work zone activities. For instance, there were cases where the same event ID was assigned to events at locations on several routes and thus all the events with the same ID were combined to become a single work zone. However, from a safety analysis standpoint, the locations scattered across the different routes should have been regarded as different work zones. Although such cases were found in the VaTraffic database, the vast majority of the cases was assessed to be reliable for analysis.
Matching Work Zone Crashes and Events

The work zone crash dataset was matched with the work zone activity dataset using the location and temporal information in both datasets. The work zone crash dataset included date, time, route, and mile point of a work zone crash, and the work zone activity dataset included start and end mile points and start and end times/dates of a work zone event. Therefore, a work zone crash was successfully matched to a work zone event when the location of the crash was within the bounds of the work zone event and the time of the crash was within the specified time period of the work zone event.

The matching rate between work zone crashes and work zone events from the two datasets was low. Various matching algorithms were developed and tested to increase the matching rate. For example, the work zone’s physical limits recorded in the VaTraffic database were extended upstream and downstream to address any possible inaccuracy in the locational information in either the police crash report or the VaTraffic data entry and to capture crashes that occurred in work zone queues. The matching rate increased to some extent but was not high enough to proceed for analysis. Further refinements to the matching algorithm were considered to be impractical because preparing the work zone activity dataset using a sophisticated algorithm was expected to be time-consuming and should be performed on a regular basis to calculate rate-based metrics if the metrics were determined to be used as statewide work zone safety performance measures for Virginia.

Because of the data integration issue described, calculating crash exposures and rates was determined to be impractical for implementation for individual work zones. Although the work zone crash and activity datasets were not well matched at an individual work zone, the work zone activity dataset could still be used for calculating exposure and rate measures at a geographically aggregate level such as district, region, and state. For example, aggregating the work zone activity dataset across the entire state over a year would produce statewide annual work zone activity statistics such as the annual total number of work zones statewide. Such aggregate work zone exposure measures would be a reliable indicator of overall work zone activity in the state, even if the absolute value was not accurate.

Estimating Work Zone Traffic Volumes

Crash exposures frequently used in traffic safety studies such as AADT and VMT are based on traffic volume. An ideal way of capturing these exposures for work zone safety assessments is to collect traffic volumes at a work zone site continuously throughout the entire duration of the work zone activities. In many cases, traffic volumes at a site may change during work activities, especially if the work zone creates congestion. Real-time monitoring using automated traffic monitoring devices would allow for any changes to be captured. Unfortunately, many work zone activities cause existing detectors to be removed, and it is impractical to deploy mobile traffic monitoring devices to many work zones statewide.

Alternatively, approximate measures of AADT and VMT can be derived using existing and readily available data sources. VDOT estimates annual AADTs for all roadways in the state, and they are recorded in the TMS database. If accurate information on the physical and temporal limits of the work zone is known, it may be possible to calculate an estimate of AADT by combining the work zone information with traffic volume data in the TMS database. Since many of the AADT estimates in TMS are based on factored short-term counts, this approach would assume that work zone activities do not change traffic demand, however.
As noted earlier, there was an issue in matching the work zone crash and activity datasets. With the matching issue with regard to the study data, identifying appropriate work zone road segments from which to obtain AADT data in the TMS database was a challenge encountered during the study. However, as discussed previously, aggregating relevant data over a fairly large geographic area could turn these data into useful information for calculating work zone safety performance measures.

In the search for alternative ways to calculate approximate traffic volumes of work zones, a series of issues was noted. For example, a set of adjustments is needed to estimate traffic volumes for work zones set up for a short period and involving a lane closure. Since an AADT at a roadway segment represents an average of an entire year, it should be adjusted for the time period of the work zone to estimate a traffic volume for the work zone. In addition, capacity reductions resulting from lane closures at the work zone require further adjustments to the AADT. Although it would be possible to use an adjustment factor based on reasonable engineering judgment, the fact that several factors would be required resulted in a determination that this approach was inappropriate. As a result, estimating traffic volumes for work zones using the TMS database was not pursued. This means that outcome-based exposure (e.g., traffic volume and VMT) and corresponding rate measures (e.g., work zone crashes per million VMT) were excluded from consideration for analysis.

**Final Dataset**

The data limitations discussed earlier, especially the limitations of the work zone activity data, greatly affected the performance measures and exposure metrics that could be examined. Four count measures were calculated using the work zone crash dataset: (1) total work zone crash count, (2) total person count involved in work zone crashes, (3) fatal and injury work zone crash count, and (4) fatality and injury person count involved in work zone crashes. Four exposure measures were calculated using the work zone activity dataset: (1) work zone count, (2) work zone-miles, (3) work zone-hours, and (4) work zone-hour-miles; these are output-based measures. For example, work zone-hour-miles were computed by summing the duration of a work zone in hours and then multiplying by the length of the work zone in miles over all identified work zones, as shown in Equation 1:

\[
\sum_i Hours_i \times Miles_i
\]

where \(i\) = work zone index. The count and exposure measures were prepared in four temporal settings: annual, biannual, quarterly, and monthly. Moreover, these measures were prepared for the entire state and by VDOT construction district for separate analyses. As noted earlier, outcome-based exposure measures involving traffic volume such as AADT and VMT were not included for data analysis because of data limitations.

Although the count measures of work zone crashes have been calculated by VDOT since 2004, the work zone activity dataset exists only for work zones occurring after mid-2008 when the VATraffic system was launched. Although data began being entered into the VaTraffic system in 2008, it is believed that stable data entry practices were not until the end of 2008. Thus, the exposure measures calculated using 2008 VaTraffic data were removed, resulting in 5 years (2009-2013) of statewide data. The statewide data were prepared for three road networks: all roads, interstate highways, and non-interstate state-maintained highways.
In the end, a total of 16 separate datasets (12 statewide datasets and 4 district-specific datasets) were formed for analysis: four temporal settings (annual, biannual, quarterly, and monthly) multiplied by three road types (all roads, interstates, and non-interstates) for the statewide data and four temporal settings multiplied by one road type (all roads) for the district-specific data. District data were not separated by road type because the sample size of the resulting data became an issue for some districts.

Table 1 provides descriptions and basic statistics of the variables used in the final dataset, and definitions of the variables are identical across the 16 separate datasets except for temporal and geographic units. Values of the variables differ by the dataset corresponding to each of the 16 different combinations of the temporal and geographic levels. For example, in the district-level quarterly dataset, ALLCRH corresponds to the number of total work zone crashes that occurred in a specific quarter in a specific year in a specific district whereas in the statewide annual interstate dataset, it corresponds to the number of total work zone crashes that occurred in a specific year on interstate highways in Virginia. Rate measures were calculated using the variables after statistical analyses were completed.

Descriptive statistics of 2009-2013 annual and quarterly datasets for all roads are provided to offer a general sense of the study datasets. On average, about 3,400 work zone crashes were reported annually across Virginia and about 7,000 persons were involved in those crashes. It should be noted that drivers in the crashes are reported regardless of their injury level yet only non-drivers sustaining at least minor injury are reported by the police in Virginia. There were about 28,000 work zones per year across the state, amounting to about 1.6 million hour-miles of work zone activities annually.

### TABLE 1 Variable Description and Descriptive Statistics (2009-2013)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Variable Description</th>
<th>Annual Statistics&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Quarterly Statistics&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Type</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>ALLCRH</td>
<td>Number of all work zone crashes</td>
<td>3,187</td>
<td>465</td>
<td>797</td>
<td>253</td>
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<tr>
<td>ALLPER</td>
<td>Number of all persons at work zone crashes</td>
<td>7,030</td>
<td>1,075</td>
<td>1,757</td>
<td>546</td>
</tr>
<tr>
<td>FIJCRH</td>
<td>Number of fatal and injury work zone crashes</td>
<td>1,117</td>
<td>149</td>
<td>279</td>
<td>89</td>
</tr>
<tr>
<td>FIJPER</td>
<td>Number of fatal and injury persons at work zone crashes</td>
<td>1,645</td>
<td>241</td>
<td>411</td>
<td>137</td>
</tr>
<tr>
<td>WKZCNT</td>
<td>Number of work zones</td>
<td>26,546</td>
<td>5,848</td>
<td>6,637</td>
<td>1,908</td>
</tr>
<tr>
<td>WKZHOU</td>
<td>Number of work zone-hours&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1,290,995</td>
<td>211,429</td>
<td>322,749</td>
<td>79,729</td>
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<tr>
<td>WKZMIL</td>
<td>Number of work zone-miles&lt;sup&gt;d&lt;/sup&gt;</td>
<td>105,662</td>
<td>21,534</td>
<td>26,416</td>
<td>7,097</td>
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<tr>
<td>WZHOMI</td>
<td>Number of work zone-hour-miles&lt;sup&gt;e&lt;/sup&gt;</td>
<td>1,565,921</td>
<td>271,973</td>
<td>391,480</td>
<td>113,434</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on 5 yearly observations.

<sup>b</sup> Based on 20 quarterly observations.

<sup>c</sup> $\sum_i Hours_i$ where $i =$ work zone index.

<sup>d</sup> $\sum_i Miles_i$ where $i =$ work zone index.

<sup>e</sup> $\sum_i Hours_i \times Miles_i$ where $i =$ work zone index.
METHODS

Linearity Condition
For a rate to serve as a reliable safety performance measure, its numerator (i.e., count) should have a linear relationship with its denominator (i.e., exposure), hereinafter called the linearity condition, under the assumption that only the exposure has a significant impact on the count. Although this assumption cannot be entirely true in reality, especially for traffic safety, it is often reasonable when there are no major abrupt changes in vehicle design, road geometry, highway design standards, enforcement activities, or safety-related laws and policies. In that case, no substantial changes in crash counts are expected as long as exposure measures such as traffic volume, road user population, and/or registered vehicles remain the same.

The following example may be considered: Suppose two roads are identical in all important characteristics influencing safety (e.g., traffic volume, speed limit, geometry, road users, and weather) except that one road is twice as long as the other. The longer road is naturally expected to have double the crashes of the shorter one during the same time period. In this case, the length satisfies the linearity condition and, thus, can serve as a normalizing exposure to produce a reliable rate measure such as crashes per mile; thus, the two roads would be identical in their safety performance measured in a crash rate per mile.

For work zone safety, there appears to have been no major changes in work zone safety management practices, policies, and/or enforcement activities in Virginia that substantially and abruptly influenced work zone safety conditions statewide since 2009. Thus, the linearity condition could be used to identify pairs of count and exposure measures suitable for calculating rates for work zone safety in Virginia. Technically, a pair of count and exposure measures that shows a strong linear relationship would be a good candidate for calculating a reliable rate measure. In the case of this study, this linear relationship would establish that even though the work zone activity dataset has known limitations, it still represents a reasonable surrogate measure of overall work zone activity in the state.

Linear Regression
A regression analysis with a linear functional form was used to identify rate measures suitable for work zone safety performance measures. A count measure was regressed on an exposure measure, meaning that the count and the exposure enter into a regression equation as dependent and explanatory variables, respectively, in a linear fashion. Equation 2 shows a regression model specification:

\[ Y = a + bX \]  \hspace{1cm} (2)

where \( Y \) = a count measure, \( X \) = an exposure measure, and \( a, b \) = intercept and slope coefficients to be estimated, respectively. If the slope coefficient estimate \( b \) is found to be statistically significant, a pair of a count and an exposure in the model would be determined to be eligible for consideration as a rate measure. For example, Equation 3, a regression equation,

\[ \text{Number of Work Zone Crashes} = a + b \times \text{Number of Work Zones} \]  \hspace{1cm} (3)

with a statistically significant \( b \) leads to a rate measure, i.e., work zone crashes per work zone, which is deemed to be an eligible performance measure.
Figure 1 illustrates the linearity condition using the quarterly statewide dataset of non-interstate highways in Virginia. As seen in the scatterplot of Figure 1(a), the relationship between the quarterly numbers of work zones and work zone fatalities and injuries is linear. The fitted linear regression confirmed that the linear relationship is statistically significant ($p < 0.001$) and strong ($R^2 = 0.80$). This implies that the linear condition is met for the pair of the count and exposure measures. Accordingly, the rate derived from the pair (work zone fatalities and injuries per work zone) is eligible to be a work zone safety performance measure at a quarterly level.

(a) Quarterly numbers of work zones vs. work zone crash fatalities and injuries.

(b) Quarterly numbers of work zone-hour-miles vs. work zone crashes.

**FIGURE 1** Illustrative examples for the linearity condition (non-interstate highways). The solid line represents a fitted linear regression, and triangles represent actual data.

On the other hand, in Figure 1(b), the relationship between work zone-hour-miles and work zone crash counts looks linear but it seems weak. The regression results confirmed this visual assessment in that the slope coefficient estimate is not statistically significant at the 0.05 level but is significant at the 0.1 level and is weak ($R^2 = 0.25$). This means that work zone crashes per work zone-hour-mile is not likely to be eligible to be a statewide safety performance measure of work zones at a quarterly level. What this implies is not necessarily that there is no
relationship between work zone crashes and work zone-hour-miles, rather it means that the
inherent limitations in the VaTraffic exposure data do not make this a good surrogate exposure
measure for work zones. Inaccuracies in recorded work zone bounds or durations may limit the
use of those particular measures for this temporal level of aggregation.

Suitability Index

To select suitable rates based on the statistical results varying across the four temporal levels, a
weighting scheme was devised to produce a single index, called the suitability index in this study.
A threshold value for a rate to be suitable was set at 5. The suitability index is calculated as
shown in Equation 4:

\[
\text{Suitability Index} = 5 \times I(\text{Annual}) + 4 \times I(\text{Biannual}) + 3 \times I(\text{Quarterly}) + 1 \times I(\text{Monthly})
\]  (4)

where \( I(\cdot) \) equals 1 if a regression corresponding to the temporal level specified in the
parenthesis is statistically significant at the 0.05 level and 0 otherwise; 5, 4, …, 1 are weights.
The weight values were determined based on logical considerations. A higher weight indicates
that a higher importance is given to a regression based on more aggregated data (e.g., annual data
being more aggregated than quarterly data) so that a chance for a rate corresponding to the
regression to be suitable is higher.

The suitability index threshold of 5 was chosen to disqualify a rate with corresponding
regressions being statistically significant only at the quarterly and/or monthly level; thus,
regressions that were not statistically significant for both annual and biannual data were excluded
from consideration. With the suitability index calculated and the threshold set at 5, a rate was
determined to be suitable even when its corresponding regression was statistically significant
only at the annual level. For example, a rate where a regression at the annual level is statistically
significant yet those at the other three temporal levels are not is still suitable because its
suitability index is 5, meeting the threshold. However, a rate where regressions are statistically
significant only at the quarterly and/or monthly level is not suitable because its index value is a
maximum of 4, failing to meet the threshold. Although the study focused mainly on suitable
safety measures at the statewide annual level, the other more disaggregate measures could be
used to obtain further insights and understanding. For example, quarterly safety measures could
provide additional information on seasonal patterns underlying the annual trends.

RESULTS AND DISCUSSION

The analysis was performed in two steps: (1) once data were formed in four temporal formats
(i.e., monthly, quarterly, bi-yearly, and yearly), a linear regression was developed for each pair
of a count being a dependent variable and an exposure being an explanatory variable (e.g., Table
2); and (2) based on the regression results, a suitability index was calculated for each of 16 pairs
leading to a set of suitable rate-based safety performance measures (e.g., Table 3).

To identify pairs of count and exposure measures suitable for developing rate measures,
the linearity condition was tested through a regression analysis for each road type (all roads,
interstate highways, and non-interstate highways) and temporal level (annual, biannual, quarterly,
and monthly). This means that 16 regressions were developed at each of four temporal levels for
each of three road types, resulting in a total of 192 regressions developed based on the statewide
data (16 regressions x 4 temporal levels x 3 road types).
### TABLE 2 Regression Results for Rate Measures for All Roads in Virginia

<table>
<thead>
<tr>
<th>Regression Variables</th>
<th>R²</th>
<th>Dependent</th>
<th>Biannual</th>
<th>Quarterly</th>
<th>Monthly</th>
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<td>WKZMIL</td>
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<td>WKZHOU</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WKZMIL</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>WKHOMI</td>
<td>0.88</td>
<td></td>
<td></td>
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</tbody>
</table>

Note: An empty cell indicates that a corresponding regression is not statistically significant in the slope coefficient estimate at the 95th percentile confidence level and 2009-2013 data were used for the analysis.

Table 2 presents R² values of the estimated regressions for all roads where the slope coefficient estimate was statistically significant at the 95th percentile confidence level. An empty cell in the table indicates that a slope coefficient estimate of a corresponding regression is not statistically significant.

### TABLE 3 Safety Performance Rate Measures for Work Zones in Virginia

<table>
<thead>
<tr>
<th>Safety Performance Rate Measures</th>
<th>All Roads</th>
<th>Interstate Highways</th>
<th>Non-Interstate Highways</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash Rates</td>
<td></td>
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<tr>
<td>Crashes per work zone</td>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Crashes per work zone-hour</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Crashes per work zone-mile</td>
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<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Crashes per work zone-hour-mile</td>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Person Rates</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Persons per work zone</td>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Persons per work zone-hour</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Persons per work zone-mile</td>
<td>×</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Persons per work zone-hour-mile</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fatal &amp; Injury Crash Rates</td>
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<td></td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>Fatal &amp; injury crashes per work zone-hour</td>
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<tr>
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<td>×</td>
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<td>×</td>
<td>×</td>
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<td>Fatality &amp; Injury Rates</td>
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</tr>
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<td>×</td>
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</tr>
<tr>
<td>Fatalities &amp; injuries per work zone-hour</td>
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<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Fatalities &amp; injuries per work zone-mile</td>
<td>×</td>
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<td>✓</td>
</tr>
<tr>
<td>Fatalities &amp; injuries per work zone-hour-mile</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
</tbody>
</table>

Note: ✓ indicates suitable and × indicates not suitable based on the suitability index, Equation 4.

Table 2 presents R² values of the estimated regressions for all roads where the slope coefficient estimate was statistically significant at the 95th percentile confidence level. An empty cell in the table indicates that a slope coefficient estimate of a corresponding regression is not statistically significant.
not statistically significant at the 0.05 significance level, meaning failure to meet the linearity condition. For example, the independent variable WKZCNT was found to have a linear relationship with the dependent variable ALLCRH in the annual, biannual, and monthly datasets but not in the quarterly dataset. It was noted that a reported $R^2$ value decreases as the temporal level becomes less aggregate mainly because a less aggregate dataset has more observations and larger variation.

Estimated results for interstate and non-interstate highways revealed differences between the two road categories although they are not shown here because of limited space (see Kweon et al. [2] for the results). For example, a rate of total crashes per work zone corresponding to a regression of ALLCRH on WKZCNT was found to be suitable to serve as a safety performance measure for interstate highways but not suitable for non-interstates based on an analysis of the annual dataset. In general, regressions involving hour-related exposures (i.e., work zone-hours and work zone-hour-miles) as an independent variable were found to be statistically significant. This means the hour-related exposures have a linear relationship with the count measures (i.e., the linearity condition is satisfied). This further implies that a rate measure employing an hour-related exposure as its denominator is generally suitable for a safety performance measure of work zones. Even with the data limitations of the VaTraffic database, the duration measure still seemed to serve as a reasonable surrogate for overall exposure of work zones in Virginia.

Table 3 shows the 16 rates, indicating which are suitable rate measures using the suitability index and threshold values. For all roads, 11 rates were determined to be suitable and all 4 rates involving work zone-miles were found not to be suitable. For interstate highways, seven total crash or person rates were suitable but no fatal and injury rates were suitable. For non-interstate highways, 14 rates were suitable except for two rates involving work zone-miles. It is noted that rates reflecting only fatal and injury crashes are not appropriate for interstate highways and most rates regardless of injury severity tended to be suitable for non-interstate highways. Moreover, rates based on work zone-hour-mile reflecting all three output-aspects of work zones (count, duration, and length) tended to be better than those based on work zone-hours and work zone-miles as safety performance measures.

**Implementing Rate-Based Safety Performance Measures**

Table 3 shows the suitable rate measures based solely on data analysis results. However, practical perspectives should also be considered in conjunction with such results when safety performance measures are determined for actual implementation for the work zone safety program of a highway agency. For example, it was necessary to define a fairly small number of safety performance measures to make calculation as simple and easy as possible for VDOT.

The analysis results and the suitable rate measures were reviewed by VDOT work zone safety personnel in the central office and districts to determine which measures had broad support. Based on this review, VDOT adopted four performance measures for its work zone safety program (see Kweon et al. [2] for details). The four performance measures included two count measures and two rate measures (total and fatal/injury work zone crashes per million work zone-hour-miles). The two rate measures were based on the exposure reflecting the statewide count, temporal duration, and physical length of work zones. Figure 2 shows the total work zone crashes per million work zone-hour-miles updated to cover the most recent 5 years in Virginia: 2011-2015. According to this rate measure, work zones in Virginia performed similarly with regard to the safety performance measures in the first 3 years, i.e., 2011-2013. These measures decreased substantially for work zones on interstate highways in 2014 followed by a
considerable improvement in 2015. The performance measures for non-interstate work zones have remained stable over the past 5 years. Further information on Virginia’s work zone safety conditions are found in 2011-2015 Virginia Work Zone Crash Facts (13).

One of the primary purposes of safety performance measures is to detect a change in traffic safety performance large enough to warrant an in-depth investigation of causes or contributing factors to changes in crashes so that actions to improve traffic safety can be devised. In this aspect, the rate measure shown in Figure 2 fully served its purpose and prompted the need for a detailed analysis of data focusing on the last 2 years to learn the reason statewide work zone safety changed in 2014 and 2015, respectively.

CONCLUSIONS
This study focused on developing and improving statewide metrics measuring work zone safety performance in Virginia, especially at the annual level. The study successfully merged different data sources such as the crash database and the VaTraffic database containing work zone activity information by aggregating individual records at four temporal levels. Based on regression analysis results and a suitability index designed to select reliable rates for safety performance measures of work zones, the study developed rate measures to be used as statewide safety performance measures of work zones. Based on the analysis results, the following four conclusions were drawn:

1. Even though the database that recorded work zone activities had limitations, this study showed that it could still be used as a surrogate measure of exposure. Since gathering highly accurate data on work zone exposure has consistently been a challenge for states, this study showed that a methodology can be developed that will account for exposure even with imperfect data. This provides a potential mechanism to start to account for differences in work zone exposures with available data and develop performance measures to use alongside the more commonly used count measures.

2. Appropriate rates measuring statewide safety performance of work zones are different between interstate and non-interstate highways, implying data should be analyzed separately for the two highway types to determine appropriate statewide rate-based safety performance.
measures. For interstate work zones, the rates reflecting all crashes are appropriate yet those
reflecting only fatal and injury crashes are not. For non-interstate work zones, most of the rates
regardless of severity level are appropriate.

3. Rates based on the exposure (work zone-hour-miles) reflecting all three output aspects of
work zones (count, temporal duration, and physical length) appear to be better than those based
on the exposures reflecting two aspects such as work zone-hours or work zone-miles.

4. Rates based on the count of work zones seem better than rates based on the exposures
reflecting two aspects: work zone-hours or work zone-miles. This means if obtaining work zone
exposures reflecting all three aspects is not feasible, rates based on only the count of work zones
would be better than those based on work zone-miles or work zone-hours in general. This could
be in part driven by limitations in the data studied, and results may vary depending on the
accuracy of work zone activity logs at a specific state.

The conclusions are valid for statewide annual safety performance measures of work
zones and may not be valid for measures at different geographical and/or temporal levels such as
district-level or monthly measures. It should be noted that the source of the work zone activity
data, the VaTraffic system, was not designed to measure work zone exposure. However, work
zone activity data from the system are determined to be applicable in calculating exposures when
they are aggregated across the entire state over a year, although calculating exposures at an
individual work zone is not appropriate at the current level of data accuracy for the system. It is
expected that more accurate logging of work zone activities would improve the quality of these
performance measures, and Virginia should continue to push for improvements in data systems
to improve the quality of the measures. In conclusion, it is the opinion of the authors that
existing data, even if imperfect, could still be used to account for exposure within work zone
performance measures and appropriate rate measures based on exposure could be developed for
statewide work zone safety performance measures.

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REFERENCES