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Work Zone Safety Performance Measures for Virginia

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16. Abstract:

The Virginia Department of Transportation (VDOT) is interested in refining work zone safety performance measures so that safety can be better assessed, monitored, and compared over time. VDOT currently uses the number of fatalities and the number of serious injuries in work zone traffic crashes as statewide performance measures. Although these are important direct safety metrics, they do not reflect differences in work zone exposure measures, such as the number of work zones. As a result, it is not always clear whether changes in work zone crashes are being caused by safety problems or changes in the amount of road work.

This study developed and improved statewide work zone safety performance measures for Virginia by combining information from two sources in VDOT: the VDOT crash database containing information in police crash reports and the Virginia Traffic Information Management System (VaTraffic) database containing information on incidents, work zones, weather conditions, etc. Count measures, such as the number of fatal work zone crashes, were calculated from the crash database. Exposure measures, such as work zone-hours, were calculated from the VaTraffic database. Combining these two types of measures resulted in rate measures such as number of fatal work zone crashes per 1,000 work zone-hours.

Unfortunately, existing databases still have a number of limitations that prohibit the calculation of ideal rate-based performance measures. Based on currently available data, four performance measures were found to be appropriate for monitoring and evaluating the statewide safety performance of work zones, and eight summary measures were identified in order to obtain further insights regarding statewide safety issues at work zones in Virginia. These measures were selected using the results of statistical analyses and input from a technical review panel consisting of work zone coordinators and traffic engineers.

An important finding of this study was that work zone safety assessments can change significantly depending on whether exposure measures are included. Based on count measures, work zones on non-interstate highways appear to have safety records equal to or better than those on interstate highways. However, when exposure measures were incorporated, work zones on interstate highways were shown to have better safety records. This study recommends that VDOT immediately begin using the performance measures identified in this study.

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FINAL REPORT

WORK ZONE SAFETY PERFORMANCE MEASURES FOR VIRGINIA

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ABSTRACT

The Virginia Department of Transportation (VDOT) is interested in refining work zone safety performance measures so that safety can be better assessed, monitored, and compared over time. VDOT currently uses the number of fatalities and the number of serious injuries in work zone traffic crashes as statewide performance measures. Although these are important direct safety metrics, they do not reflect differences in work zone exposure measures, such as the number of work zones. As a result, it is not always clear whether changes in work zone crashes are being caused by safety problems or changes in the amount of road work.

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Unfortunately, existing databases still have a number of limitations that prohibit the calculation of ideal rate-based performance measures. Based on currently available data, four performance measures were found to be appropriate for monitoring and evaluating the statewide safety performance of work zones, and eight summary measures were identified in order to obtain further insights regarding statewide safety issues at work zones in Virginia. These measures were selected using the results of statistical analyses and input from a technical review panel consisting of work zone coordinators and traffic engineers.

An important finding of this study was that work zone safety assessments can change significantly depending on whether exposure measures are included. Based on count measures, work zones on non-interstate highways appear to have safety records equal to or better than those on interstate highways. However, when exposure measures were incorporated, work zones on interstate highways were shown to have better safety records. This study recommends that VDOT immediately begin using the performance measures identified in this study.

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INTRODUCTION

Background

According to the *Code of Federal Regulations* (23 C.F.R. Part 630, Subpart J) relevant to traffic safety and mobility in work zones: "States 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." The use of performance measures is a way of satisfying this requirement (Ullman and Lomax, 2011). Through the establishment of appropriate performance measures, work zone impacts can be assessed, monitored, and compared over time.

The Federal Highway Administration's (FHWA) Work Zone Mobility and Safety Self-Assessment tool also emphasizes the need for states to develop performance measures (FHWA, 2004). Performance measures are needed to be able to answer the following self-assessment questions:

- Has the agency established measures to track work zone crashes?

- Does the agency collect data to track work zone safety performance in accordance with agency-established measures?

- Does the agency develop strategies to improve work zone performance on the basis of work zone performance data and customer surveys?

- Has the agency established strategic goals specifically to reduce crashes in work zones?

VDOT's Current Work Zone Safety Performance Measures

The Virginia Department of Transportation (VDOT) currently uses the annual raw number of persons killed and the number of persons seriously injured in work zone traffic crashes as the statewide work zone safety performance measures reported in VDOT's annual reports of the Highway Safety Improvement Program (HSIP) (e.g., VDOT, 2011). Figure 1 shows the raw numbers of deaths and serious injuries in work zone crashes from 2004-2008 as reported in the FY 2011-12 annual report. In addition, the numbers regarding the type of work zone crashes over the last 12 months and the last 3 years are reported on VDOT's external Dashboard website (VDOT, 2007).

The number of fatalities and number of 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 are based on the assumption that measures of exposure such as the number, duration, and length of work zones are similar from year to year. For example, if a total of 100 traffic crashes occurred in 1 year in 100 1-mile work zones and the same number of crashes occurred in the next year in 50 1-mile work zones, although the number of work zone crashes is the same for the 2 years, the safety performance would be different for the years. As a result, although crash frequencies are easy to obtain and understand, they do not reflect information on the number, duration, 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.

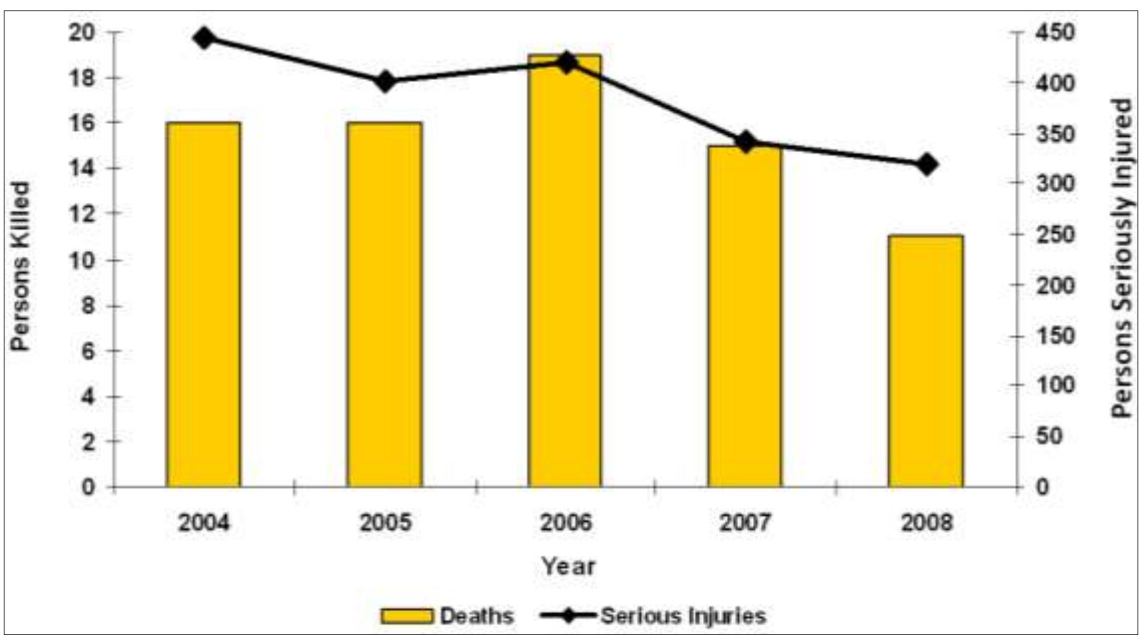


Figure 1. Annual Deaths and Serious Injuries From Work Zone Crashes in Virginia (VDOT, 2011)

Given the federal emphasis on work zone safety performance measures and the use of data-driven approaches, there is a need to develop and refine further the performance measures used by VDOT. Existing data sources need to be reviewed to determine which measures could be consistently and reliably calculated to account better for both crash frequency and exposure. Improved performance measures would allow for better tracking of work zone safety impacts and would help identify areas where additional attention might be needed to improve safety.

PURPOSE AND SCOPE

The purpose of this study was to develop improved work zone safety performance measures for Virginia. The study focused on statewide performance measures reflecting traffic crash consequences at work zones in Virginia and did not include incidents not found in police crash reports, such as workers' injuries resulting from a crash but not reported to the police. Performance measures were examined at the state or district level, and project-level performance measures were not investigated. Although performance measures were proposed, the definition of specific performance targets was beyond the scope of this study.

METHODS

Literature Review

Relevant materials were identified mostly through online resources such as TRID and reviewed. The review focused on measures that are used in practice elsewhere or have the potential to serve as performance measures. For the measures used in practice, additional information was obtained including Strategic Highway Safety Plans (SHSPs) from identified states. Guidance materials on work zone performance measures such as *A Primer on Work Zone Safety and Mobility Performance Measurement* (Ullman and Lomax, 2011) were also reviewed.

Data Preparation

A primary requirement for any performance measures selected for use is that the data needed to calculate them be readily available. As a result, the focus was on data electronically stored in VDOT databases. Four data sources in VDOT were identified as potentially useful for this study: (1) the VaTraffic database, (2) the crash database, (3) the traffic monitoring system database, and (4) the roadway inventory database.

VaTraffic, a web-based integrated data management platform, was developed by VDOT in 2008 to enhance traffic management capabilities and coordinate better a variety of roadway activities affecting the quality of travel. The system gathers and stores information on planned and unplanned events such as traffic incidents, congestion, work zones, security, and weather conditions. These events are entered into VaTraffic by authorized VDOT personnel and contractors. VaTraffic also disseminates information on the entered events and impacts of those events to internal VDOT responders and the public. VaTraffic is the most reliable source for actual, implemented work zone activities on a statewide basis.

The crash database, traffic monitoring system database, and roadway inventory database are subsystems of VDOT's Roadway Network System (RNS). The crash database (RNS_CRASH) contains historical crash records including more than 70 elements of crash-, occupant-, and vehicle-related characteristics extracted from police crash reports. The traffic monitoring system database (RNS_TMS) contains historical traffic count data for continuous count sites and short-term count locations statewide. The roadway inventory database (RNS_CORE) contains information for the approximately 62,000 centerline miles of public roads in Virginia including cross-section characteristics, functional classification, and administrative information. The roadway inventory database serves as the backbone in merging different subsystems of RNS.

Data Analysis

A combination of visual examinations, correlation analysis, and regression analysis was used to evaluate potential safety performance measures considered in this study. Count and exposure measures were examined mainly with the use of graphs showing trends over multiple years, and rate measures were primarily examined by means of linear regressions.

RESULTS AND DISCUSSION

Literature Review

Strategic Highway Safety Plans

The SHSPs of 30 states were surveyed to identify work zone safety performance measures used in practice (see Appendix A for the results). Nineteen of the plans reviewed included work zone safety in their focus areas, and the remaining 11 did not. Of the 19 that did include work zone safety, 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 [State of Maryland, 2011] and Virginia's SHSP [VDOT, 2012]).

Several states have established goals for work zone safety, but the performance measures used to quantify the goals vary. For example, California uses traffic fatality count at construction and maintenance work zones (State of California, 2006); Pennsylvania uses traffic fatality and major injury count at all work zones (Pennsylvania Department of Transportation [DOT], 2012); and New York uses fatal and injury traffic crash count at construction work zones (New York State DOT, 2010). Although goals for work zone safety were not stated, other states use various metrics in measuring and discussing work zone safety. For example, Indiana uses fatality and incapacitating injury counts at work zone crashes (Indiana DOT, 2010); Ohio uses counts of rear-end crashes caused by work zones (Ohio DOT, 2009); and Missouri uses fatality and serious injury counts and fatal and serious injury crash counts at work zone crashes (Missouri Coalition for Roadway Safety, 2012). Some states such as Massachusetts (Massachusetts DOT, 2013) and Texas (Texas DOT, 2014) specifically note that workers injured in traffic crashes are included in their metrics. Although metrics not directly measuring traffic crashes at work zones are also used, such as number of speeding tickets issued at work zones, number of work zones inspected, and percentage of inspected work zone traffic elements, the majority of work zone safety measures are counts of traffic crashes and/or crash victims at work zones.

A Primer on Work Zone Safety and Mobility Performance Measurement

The Texas A&M Transportation Institute recently published a primer on work zone safety and mobility performance measures (Ullman and Lomax, 2011). The report noted that there are two basic types of performance measures useful for quantifying safety impacts of work zones: safety measures and exposure measures. Safety measures quantify the impacts of work zones on the crash risks for an individual motorist and/or the traveling public. There are two subtypes of safety measures: outcome-based and output-based. Outcome-based measures are direct measures of crash consequences such as the numbers of crashes and crash victims and are widely used in practice (e.g., in SHSPs). Output-based measures quantify efforts or resources being deployed at work zones to improve safety, such as hours of additional law enforcement presence and amount of work zone inspection efforts. Output-based measures are not as popular as outcome-based measures, most likely because of data availability and/or efforts to acquire data.

Exposure measures are used to capture the time, roadway space, and/or vehicle travel that a work zone affects or requires. There are two types of exposure measures: outcome-based and output-based. Output-based measures quantify efforts or resources being expended such as the number of hours lanes are closed for work zone activities. Outcome-based measures quantify the level of work zone risk exposure to the traveling public, such as the number of vehicles or vehicle miles of travel (VMT) through work zones. Exposure measures alone provide useful information regarding how the frequency and characteristics of work zones change over time. They are more useful, however, when combined with the safety measures to normalize safety measures per unit exposure. Combining safety and exposure measures allows an agency to evaluate safety conditions across different work zones or those of the same work zones over time using a normalized rate, such as crashes per million VMT.

Types of Performance Measures

There are three common types of metrics useful to quantify traffic safety impacts: (1) count measures, (2) exposure measures, and (3) rate measures. Count measures are intended to measure traffic safety consequences directly (e.g., the number of work zone crash fatalities), whereas exposure measures are intended to capture the level of exposure to traffic crash risks (e.g., traffic volume and VMT). Rate measures combine the count and exposure measures, typically by dividing a count by an exposure (e.g., fatalities per million VMT), normalizing varying levels of an exposure. Thus, rate measures are generally deemed to be more reliable safety performance measures than count or exposure measures alone.

Since rate measures reflect both count and exposure measures, they are more appropriate for evaluating and comparing safety performance across areas and/or over time. Previous studies have found that statewide evaluation of safety policies and procedures is best accomplished using rate measures (Ullman and Lomax, 2011). Count and rate measures can be classified as "safety measures," whereas exposure measures are in their own category (Ullman and Lomax, 2011).

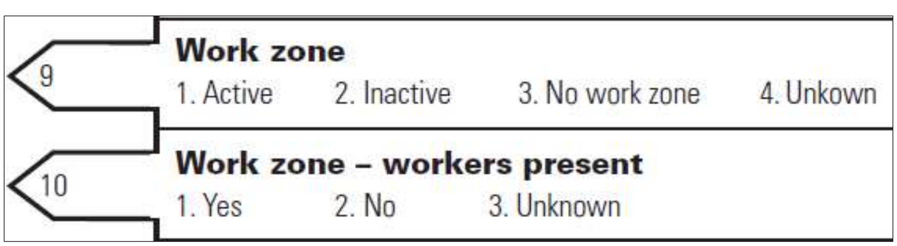
Data Preparation

Work Zone Crash Data

Three tables of VDOT's crash database were merged to form the crash dataset: CRASHDOCUMENT, CRASHVEHICLE, and CRASHPERSON. The dataset consisting of these three tables was then merged with the EYEROAD table in the roadway inventory database, resulting in the study crash dataset containing road characteristics of crash sites and crash characteristics. The EYEROAD table contains road characteristics such as maintenance jurisdiction, functional classification, and facility type. The merging process was performed using structure query language (SQL) codes executing mapping algorithms based on a linear referencing system.

Although several decades of crash data are stored in VDOT's crash database, explicit work zone information was not included in police crash reports until the revised police crash report form, FR300T (Rev 9/03), became effective in fall 2003. The revised form contains two pieces of work zone information, i.e., work zone status and worker presence, as shown in Figure 2. These correspond to two fields in VDOT's crash database: WORKZONE and WORKERSPRESENT.

Table 1 shows the distribution of coded values of WORKZONE in the crash database. Crashes having occurred in inactive work zones are believed frequently to be treated the same as no work zone crashes (WORKZONE=0) by the police in that more than 90% of all crashes found in the crash database are classified as crashes in inactive work zones: after 2009, about 97% of all crashes are coded as inactive work zone crashes.


9 **Work zone**
1. Active 2. Inactive 3. No work zone 4. Unkown

10 **Work zone – workers present**
1. Yes 2. No 3. Unknown

Figure 2. Work Zone Items on Police Crash Report Form (FR300T) (Rev 9/03)

Table 1. Traffic Crashes by Work Zone Status in VDOT's Crash Database

Year	Work Zone Status			
	Missing ( )	**No Work Zone (0)**	**Active Work Zone (1)**	**Inactive Work Zone (2)**
2001	144,470	115	0	0
2002	147,629	104	0	0
2003	154,618	225	0	0
2004	1,887	15,689	3,202	133,130
2005	1,784	7,027	3,434	141,604
2006	1	6,506	3,362	141,823
2007	2	5,874	3,151	136,377
2008	1,681	5,023	3,523	125,045
2009	677	2,119	3,254	110,069
2010	360	9	2,369	113,261
2011	108	0	3,445	116,934
2012	122	0	3,463	119,906
2013	15	0	3,404	118,190

Information in parentheses indicates the code value in VDOT's crash database.

This practice of work zone coding on police crash reports made it impossible for the research team to distinguish crashes at "true" inactive work zones from those that occurred outside of work zone areas (i.e., no work zone). From a data analyst's viewpoint, this makes two analysis schemes infeasible: (1) analysis of all work zone crashes, regardless of whether the work zone was currently active, and (2) separate analysis of active work zone and inactive work zone crashes. It was noted that the number of active work zone crashes appears stable over time. This means that the coding of an active work zone in VDOT's crash database has been reliable, at least from a statewide perspective, suggesting that active work zone crashes be the focus of analysis. Therefore, this study defined a *work zone crash* as one coded as an "active work zone" (WORKZONE=1) and analyzed data from these crashes only. It should be noted that according to the definition of *work zone crash* (Governors Highway Safety Association, 2012), all traffic crashes occurring at work zones should be identified regardless of the "active" status of the work zone.

In *1999-2003 Virginia Work Zone Crash Facts* (VDOT, 2006), a work zone crash was defined with the "road under repair" code (ROADDEFECT=4) in the roadway defect field of VDOT's crash database because there was no explicit information regarding work zones in the crash database before 2004. Annual counts of work zone crashes defined with ROADDEFECT=4 decreased from approximately 900 to 1,000 per year before 2004 to about 500 per year after 2004. Beginning in 2004, work zone crashes defined with WORKZONE=1 in the crash database have remained at or above 3,000 per year, as shown in Table 1.

Further examination of the data revealed that most of the crashes with ROADDEFECT=4 were not reported as work zone crashes based on the definition used in this study (i.e., WORKZONE=1), meaning that the two definitions of work zone crashes are not compatible after 2004. As a consequence, annual counts of work zone crashes in this study using the ROADDEFECT field and the WORKZONE field are not comparable. Thus, work zone safety statistics in *Virginia Work Zone Crash Facts* published before 2007 should not be compared to statistics in this study, which were calculated based on work zone crashes defined in accordance with the work zone information in the revised police crash report form.

Work Zone Event Data

Day-to-day reported planned and unplanned roadway activities are stored in three tables in VDOT's VaTraffic database: EVENT_MASTER, EVENT_PLANNED, and EVENT_LOCATION_SEGMENT. Standardized formats of 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), start and cleared date and time, and detection source. The EVENT_PLANNED table contains information on planned events (e.g., work zones and special events) such as detour route plan and speed limits. The EVENT_LOCATION_SEGMENT table contains detailed information on the time/sequence of events including event location, segment type, level of congestion severity (e.g., Level I, Level II, and Level III), delay type (e.g., potential, minor, and major), queue length, and number of lanes closed.

For this study, work zone events were extracted from the EVENT_MASTER table by selecting events with an event type equaling 4 (i.e., work zone events). These were then joined with the EVENT_PLANNED and EVENT_LOCATION_SEGMENT tables to append detailed information on the selected events, resulting in the study work zone event dataset. The event ID was used as a primary key for these joining tasks, and customized SQL codes were developed to prepare the work zone data. For this study, an *individual work zone* was defined as an event with a unique event ID and an event type of "work zone" in VDOT's VaTraffic database.

Data Issues

The research team found three types of issues while preparing data for analysis, as described here.

Work Zone Event Data

As described previously, this study defined a *work zone* as an event with an event type of "work zone" in VDOT's VaTraffic database. Work zone events with the same event ID were combined and considered to have occurred within a single work zone. While validating work zone events, the research team found that there are variations in how event IDs are created and assigned for work zone activities. For example, a multiday pavement marking project could require a temporary work zone setup for which the location would change each day as the project advanced. In some cases, a separate event ID number would be created and assigned to each day of the marking project, resulting in multiple work zones for the same project. In other cases, a single event ID number would be created and assigned to the entire marking project, resulting in just one work zone for the same project. Both situations were observed in the data, and it was not possible to convert these varying coding practices into one consistent method of recording work zones because of data limitations. As a result, the count of work zones available was driven, in part, by the manner in which multiday events are entered into VaTraffic by the VDOT regions.

Matching Work Zone Crash and Event Datasets

An attempt was made to match the study crash dataset containing both crash and site characteristics with the work zone dataset using the location and temporal information in both datasets. The crash dataset includes date, time, route, and mile point of a traffic crash, and the work zone dataset includes start and end mile points and start and end time and date of the work zone. Therefore, a crash is successfully matched to a work zone when the location of the crash lies within the bounds of the work zone and the time of the crash is within the specified time period of the work zone.

The starting and ending locations and times of work zones were successfully extracted from VDOT's VaTraffic database for matching against traffic crashes reported to have occurred in active work zones. Only about 20% of work zone crashes reported in VDOT's crash database could be successfully matched to work zone events in VDOT's VaTraffic database. Various matching algorithms were developed and tested to increase the percentage of identified work zone crashes that matched VaTraffic data. For example, the work zone's physical limits recorded in VDOT's VaTraffic database were extended both upstream and downstream to address possible inaccuracies in locational information in either the police crash report and/or the VaTraffic data entry. The percentage of identified crashes increased to some extent but was still found to be inadequate. Based on these results, improving the matching algorithm further was determined to be impractical mainly because preparing exposure data using the sophisticated algorithm was expected to be very time-consuming and should be performed on a regular basis, at least once a year.

This matching issue prevented work zone information from VDOT's VaTraffic database from being used to calculate performance metrics such as exposure and rate measures at an individual project or work zone. Although work zone crash and event data were not well matched at a project level, work zone event data could still be used for calculating exposure and rate measures at a geographically aggregate level such as district, region, and state. For example, aggregating work zone event data across the entire state over 1 year would produce statewide annual work zone statistics such as the total numbers of work zones and annual average daily traffic (AADT) in the state in that year. These statistics could then be used as exposure measures or in the calculation of rate measures involving these exposures.

Estimating Work Zone Traffic Volumes

Crash exposures frequently used in traffic safety studies include traffic volume such as AADT and VMT. An ideal way of capturing these exposures is to collect them at a work zone site continuously throughout the duration of the work zone activities. In many cases, traffic volume 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 detected. Unfortunately, many project activities (such as repaving) will cause existing detectors to be removed, and it is often impractical to install new detection to monitor the work zone during congestion, especially on a statewide basis.

Alternatively, approximate measures of AADT and VMT can be derived using existing and readily available data. For example, VDOT maintains a large amount of AADT data in the RNS_TMS database. If accurate information on the physical and temporal limits of the work zone is known, it should 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 is an issue in matching crash records and work zone event data at present. Without accurate information on the location of the work zone, it is not possible to identify the appropriate links from which to obtain AADT data in the RNS_TMS database. 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. It should be noted that VaTraffic was not designed with compatibility with RNS subsystems in mind, and data referencing systems of the VaTraffic and RNS_TMS databases are fundamentally different.

In searching for alternative ways to calculate approximate traffic volumes of work zones, the research team noted a series of issues that prevented them from further exploring the potential use of the RNS_TMS database for this purpose. For example, a set of adjustments is needed to estimate traffic volume for a work zone 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 work zone lane closures 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 RNS_TMS database was not pursued. This means that exposure and rate measures based on traffic volume such as work zone VMT and work zone crashes per million VMT were excluded from consideration for analysis.

Final Study Data for Performance Measure Development

Four count measures were calculated using the work zone crash data: (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 count involved in work zone crashes. Four exposure measures were calculated using the work zone event data: (1) work zone count, (2) work zone-miles, (3) work zone-hours, and (4) work zone-hour-miles. As described previously, exposures involving traffic volume such as AADT and VMT were not included for data analysis. For example, work zone-hour-miles were computed by summing the hours a work zone was active multiplied by the length of the work zone in miles over all identified work zones:

$$\sum_i Hours_i \times Miles_i$$

where

i = work zone index.

These count and exposure measures were prepared in four temporal settings, i.e., annual, biannual, quarterly, and monthly, and were combined by the temporal setting. Moreover, these measures were prepared for the entire state and by district for separate analyses.

Although the count measures of work zone crashes since 2004 can be calculated, the work zone event data exist only for work zones occurring after mid-2008, when VaTraffic was launched. Although data began being entered into VaTraffic in 2008, stable data entry practices are believed not to have been established 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 types: all roads, interstate highways, and non-interstate highways.

Although 2009 was thought to be more stable in terms of VaTraffic data entry practices, it could still be viewed as an adaptation period for VDOT personnel and contractors to this new system. Thus, a separate dataset excluding 2009 was also prepared for additional analysis. In the end, a total of 32 separate datasets (24 statewide datasets and 8 district-specific datasets) were formed for analysis: 4 temporal settings (annual, biannual, quarterly, and monthly) $\times$3 road types (all roads, interstate highways, and non-interstate highways) $\times$2 data periods (2009-2013 and 2010-2013) for the statewide data and 4 temporal settings $\times$ 2 data periods for the district-specific data. District data were not separated by road type because the resulting data did not seem reliable enough for further analysis.

Table 2 provides descriptions of the variables used in the final study data. Rate measures were calculated using the variables after statistical analyses were completed. Values of the variables differ by the dataset corresponding to each of the 32 different combinations of the temporal and geographic levels. For example, in the district-level quarterly 2009-2013 dataset, ALLCRH corresponds to the number of all work zone crashes that occurred in a specific quarter in a specific year in a specific district in the 2009-2013 years whereas in the statewide annual 2010-2013 dataset for interstate highways, it corresponds to the number of all work zone crashes that occurred in a specific year on interstate highways in Virginia in the 2010-2013 years.

Table 2. Variable Description of the Study Data

Name	Description	Type	Data Source
ALLCRH	Number of all work zone crashes	Count Measure	Crash Database
ALLPER	Number of all work zone crash persons		
FIJCRH	Number of fatal and injury work zone crashes		
FIJPER	Number of fatal and injury work zone crash persons		
WKZCNT	Number of work zones	Exposure Measure	VaTraffic Database
WKZHOU	Number of work zone-hours[a]		
WKZMIL	Number of work zone-miles[b]		
WZHOMI	Number of work zone-hour-miles[c]		

[a] $\sum_i Hours_i$ where i = work zone index.
[b] $\sum_i Miles_i$ where i = work zone index.
[c] $\sum_i Hours_i \times Miles_i$ where i = work zone index.

Evaluation of Suitable Rate Measures

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.

For example, if two roads are identical in all important aspects 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 in the recent past have substantially and abruptly influenced work zone safety conditions statewide. 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 based on empirical data collected in the recent years. Technically, a pair of count and exposure measures that shows a strong linear relationship would be a good candidate for calculating a reliable rate performance measure.

A regression analysis with a linear functional form was performed to identify rate measures suitable for a work zone safety performance from a statistical standpoint. 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. The following shows a regression model specification:

$$Y = a + bX$$

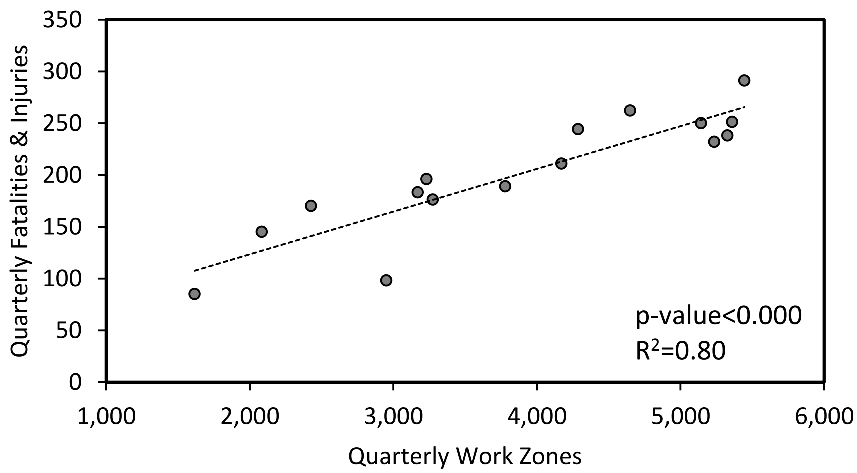
where Y = a count measure, X = an exposure measure, and a, b = intercept and slope coefficients to be estimated, respectively. If the slope coefficient estimate was found to be statistically significant, a pair of a count and an exposure in the model is determined to be suitable for a reliable rate measure. For example, a regression equation

$$Number\ of\ work\ zone\ crashes = a + b \times Number\ of\ work\ zones$$

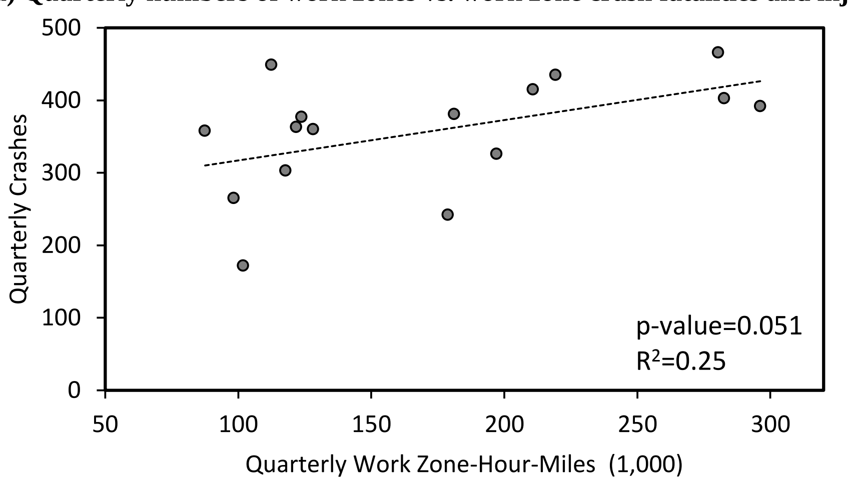
with a statistically significant b leads to a suitable rate measure: work zone crashes per work zone.

Figure 3 illustrates the linearity condition using 2010-2013 quarterly work zone data for non-interstate highways in Virginia. As seen in the scatterplot of Figure 3(a), a relationship between the quarterly numbers of work zones and fatalities and injuries at work zone crashes appears linear. The fitted linear regression confirmed that the linear relationship is statistically significant (*p*-value of the slope coefficient estimate < 0.0001) 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 determined to be suitable for a work zone safety performance measure at a quarterly level.

In Figure 3(b), a relationship between work zone-hour-miles and work zone crash counts appears linear to some degree yet insubstantial. The regression results confirmed this visual assessment in that the slope coefficient estimate was not statistically significant at the 0.05 level but was significant at the 0.1 level and was weak ($R^2 = 0.25$). This means that work zone crashes per work zone-hour-mile is not suitable for a statewide safety performance measure of work zones 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 3. Illustrative Examples for Linearity Condition (Non-Interstate Highways). The dotted lines represent a fitted linear regression, and the gray dots represent actual data.

Data Analysis

Data were prepared in SPSS 22, and most data analysis was performed in R 3.1.1. Analysis was performed for each of the three types of performance measures (count, exposure, and rate), and the results are presented in separate sections. Interstate and non-interstate highways were analyzed separately because preliminary analysis of the data revealed that their trends in the performance measures were different. Although the district-specific datasets were analyzed, their results led to the same conclusions drawn from analyzing the statewide datasets. Thus, only analysis results based on the statewide datasets are discussed.

Count Measures

The four count measures of work zone crashes being analyzed included two crash counts and two crash victim counts: (1) total work zone crash count, (2) total work zone person count, (3) fatal and injury work zone crash count, and (4) fatal and injury work zone person count. As noted earlier, only traffic crashes that occurred at work zones and were reported to the police are included in this study and non-traffic crashes at work zones such as an incident involving workers and/or equipment within a work zone are not included. Count measures are being used frequently to measure safety impacts in work zones and track trends of the impacts over time. For example, many states such as California, Pennsylvania, New York, Indiana, and Missouri use annual numbers of work zone fatalities and injuries as their work zone safety performance measures. In Virginia, the police report the total number of all injured or fatal persons and all drivers, including drivers not injured in traffic crashes. Since the total crash person count includes all persons in police crash reports, it includes uninjured drivers.

Figures 4 through 7 show trends for the four count measures by road type. Trends for interstate highways from 2009-2010 are opposite those for non-interstate highways. For example, the annual number of all work zone crashes on non-interstate highways decreased by 54% in 2010 and that on interstate highways increased by 61%; this drastic change in 2010 may be attributable to changes in work zone activities attributable to the recent economic recession. Because of the large reductions on non-interstate highways, the statewide work zone crash counts on all roads decreased in 2010 compared to 2009.

The 5-year statewide trends across the four count measures appear similar. This means that any count measure among the four would suffice in monitoring an annual trend. Analyses of quarterly data also led to the same finding, with trends being similar across the four measures (see Appendix B). However, it would be desirable to have at least two measures to capture both severity and overall crash frequency.

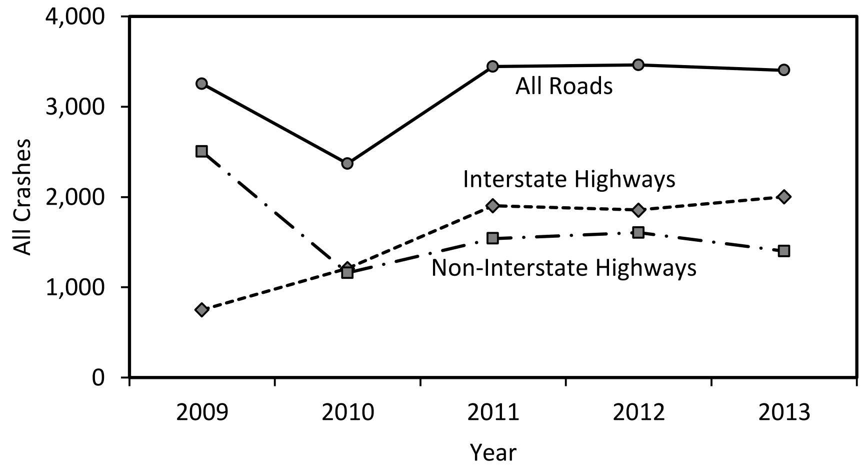


Figure 4. Annual Number of All Work Zone Crashes. Only work zone traffic crashes were counted.

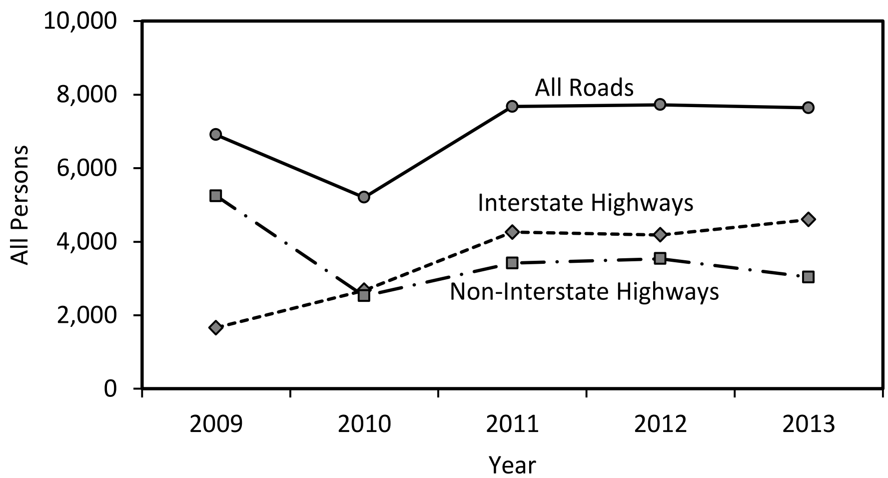


Figure 5. Annual Number of All Work Zone Crash Persons. Persons involved in a traffic crash were counted, including all drivers and injured and fatal non-drivers.

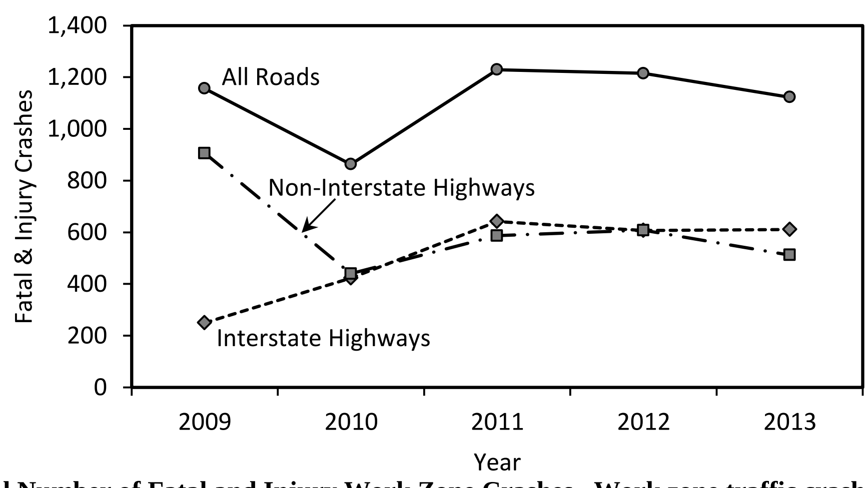


Figure 6. Annual Number of Fatal and Injury Work Zone Crashes. Work zone traffic crashes resulting in a fatality or injury were counted.

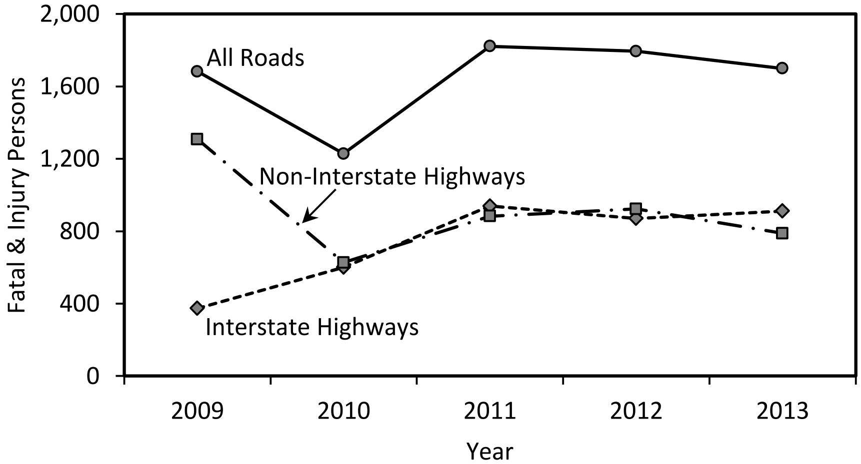


Figure 7. Annual Number of Fatal and Injury Work Zone Crash Persons. Fatal or injured persons in a traffic crash were counted.

Exposure Measures

As noted earlier, there are two types of exposure measures: outcome-based and output-based (Ullman and Lomax, 2011). The outcome-based exposure measures capture the intensity of use by the traveling public through work zones, such as traffic volume. The output-based exposure measures capture efforts or resources being expended at work zones, such as duration and length of work zones. Both types can serve as useful performance measures since they reflect different perspectives of work zone crash exposure. Thus, both were initially considered for this study. However, because of the data issues with calculating outcome-based exposure measures involving traffic volume, these exposure measures could not be empirically examined.

The four output-based exposures examined were (1) number of work zones, (2) number of work zone-hours, (3) number of work zone-miles, and (4) number of work zone-hour-miles. As noted earlier, there are some inconsistencies in the way in which data are coded in VaTraffic, both in terms of how multiday work zones are coded and the degree of agreement between the VaTraffic data and the crash data recorded in RNS. Despite these inconsistencies, there is no evidence that the manner in which work zones are recorded in RNS has changed over time. Thus, it was expected that the output-based measures would be internally consistent for tracking exposure over time, even though there may be some systematic biases in the absolute values of the data.

Since work zone-hour-miles accounts for both the temporal and physical length of a work zone, the researchers expected this measure would be the most accurate measure of work zone exposure among the four. The numbers of work zone-days and work zone-day-miles were initially included and analyzed with *a day* being defined as any day for which any number of hours was reported as "work zone" in VaTraffic. Thus, the number of days was simply counted in terms of calendar days. For example, an 8-hour event and a 1-hour event were both counted as 1 day when the event started and ended on the same calendar date. Because the definition of *a day* would introduce a potentially wide variation in the temporal exposure and exposures based on actual *hours* were found to perform similar to or better than those based on *days*, work zone-days and work zone-day-miles were excluded from consideration.

The four outcome-based statewide exposures calculated are presented in Figures 8 through 11, separated by road type. Some differences were revealed in the trends of the four exposures: their quarterly counterparts are presented in Figures B5 through B8 of Appendix B. An increasing or non-decreasing trend was found for work zone counts (Figure 8), and a trend with a substantial decrease in 2010 and a plateau after was found for work zone-hours except for interstate highways (Figure 9). An increasing trend with a slight decrease in 2012 was found for work zone-miles except for non-interstate highways (Figure 10), and a decreasing or plateaued trend with a decrease in 2010 was found for work zone-hour-miles except for interstate highways (Figure 11).

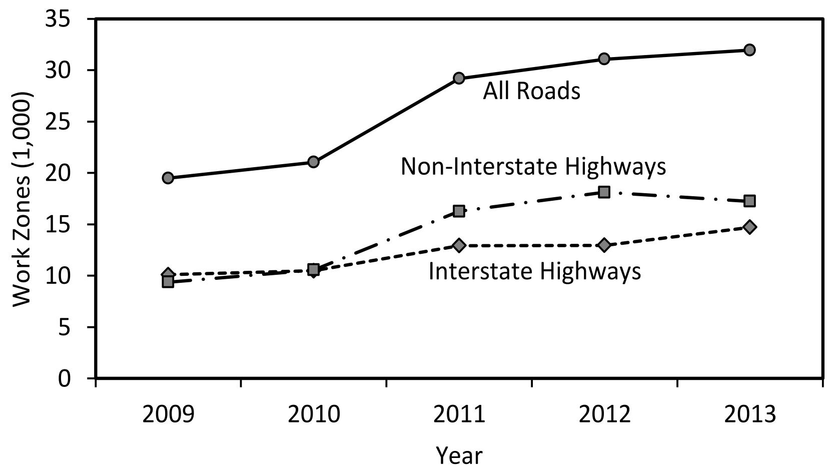


Figure 8. Annual Number of Work Zones

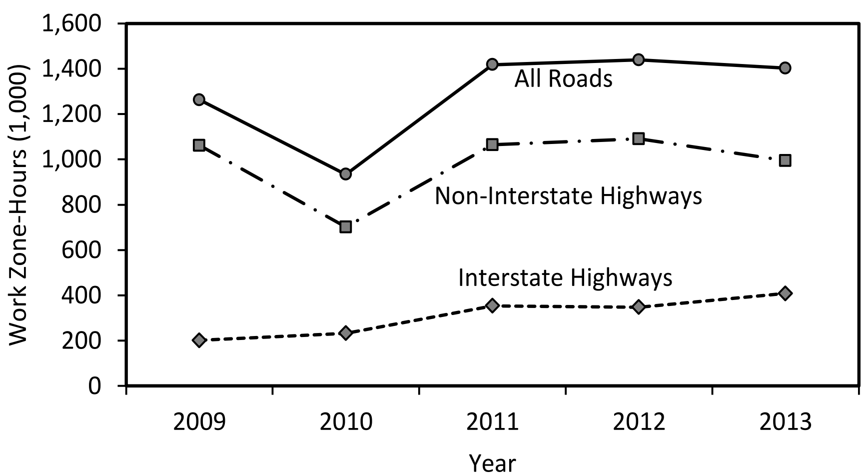


Figure 9. Annual Number of Work Zone-Hours

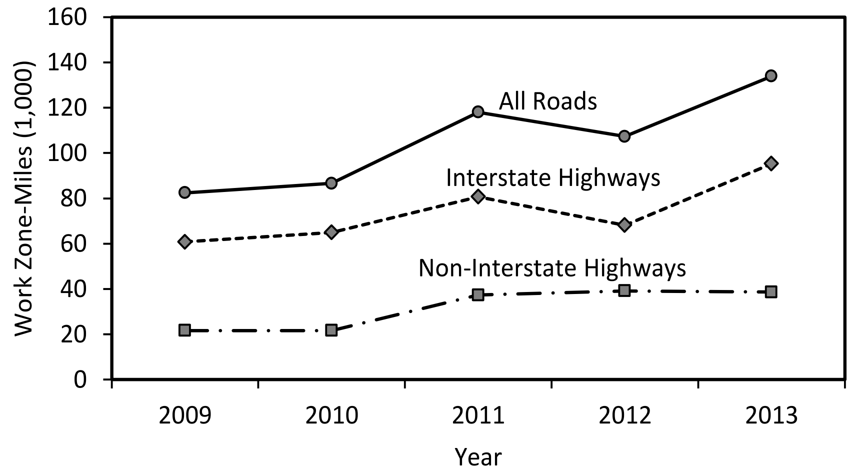


Figure 10. Annual Number of Work Zone-Miles

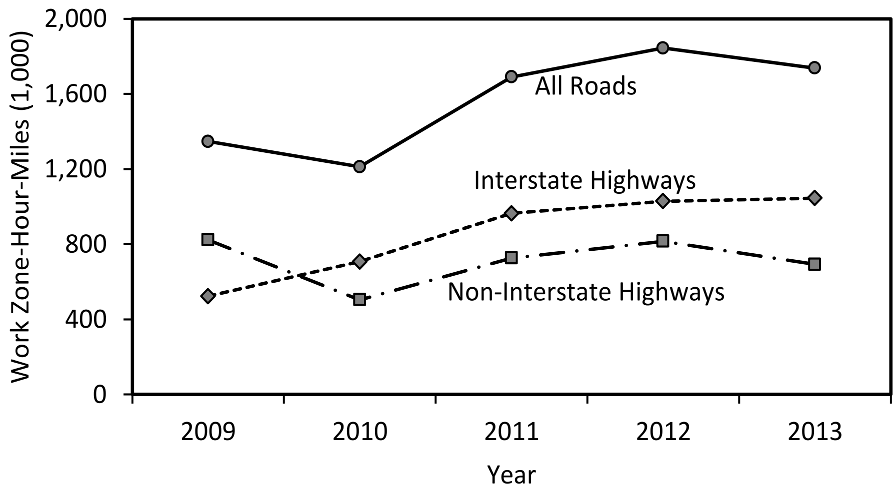


Figure 11. Annual Number of Work Zone-Hour-Miles

The non-interstate highways had about 17% more work zones (Figure 8) and more than 200% more work zone-hours (Figure 9) than the interstate highways during the 5 years. However, they had 57% fewer work zone-miles than the interstate highways (Figure 10). Thus, depending on which exposure was used (e.g., hours or miles), the non-interstate highways had a higher or lower exposure to work zone crash risk compared to the interstate highways. This suggests that an exposure reflecting both length and duration more reliably represents the level of a work zone exposure. When length and duration information was combined to produce work zone hour-miles, the non-interstate highways had about 17% fewer work zone hour-miles than the interstate highways on average (Figure 10).

It is interesting that the work zone-hours exposure measure (Figures 9 and 11) shows trends similar to those of the crash count measures (Figures 4 through 6). This similarity may suggest that a rate using a crash count measure and an exposure involving hours could satisfy the linearity condition described previously. This further suggests that rate measures involving an hour-related exposure have a higher potential to become a suitable rate measure than those involving other exposure measures.

Rate Measures

Because four measures for each of the count and exposure measure types were included in the study, a total of 16 possible rates were devised by pairing the four counts to the four exposure measures. They are presented in Table 3. The analysis for the rate measures was aimed at identifying pairs where the count was statistically related to the exposure in a linear fashion. As described previously, a regression analysis was used. Specifically, 16 regressions testing a linearity condition were formulated for the 16 rates in each of the 32 separate datasets. The results based on 4 datasets corresponding to four temporal levels (annual, biannual, quarterly, and monthly) of statewide 2009-2013 data are discussed here.

To identify suitable pairs of count and exposure measures, the linearity condition was tested through a regression analysis for each road type (i.e., all roads, interstate highways, and non-interstate highways). The condition was tested using the four temporal levels (annual, biannual, quarterly, and monthly) separately to ensure that suitable rate measures were selected. Technically speaking, this means that 16 regressions were developed at each temporal level for each road category, resulting in a total of 192 regressions developed based on the statewide data (16 regressions × 4 temporal levels × 3 road types). It should be noted that the results presented focus mainly on suitable measures at the statewide annual level. However, other, more disaggregate measures could be used to obtain further insights and understanding. For example, the quarterly count measures presented in Appendix B provide additional information on seasonal patterns underlying the annual trends.

Table 3. Possible Rate Measures of Work Zone Safety

Rate Measure[a]		Count Measure[b]	Exposure Measure[b]
Crash Rates	Crashes per work zone	ALLCRH	WKZCNT
	Crashes per work zone-hour		WKZHOU
	Crashes per work zone-mile		WKZMIL
	Crashes per work zone-hour-mile		WKHOMI
Person Rates	Persons per work zone	ALLPER	WKZCNT
	Persons per work zone-hour		WKZHOU
	Persons per work zone-mile		WKZMIL
	Persons per work zone-hour-mile		WKHOMI
Fatal and Injury Crash Rates	Fatal and injury crashes per work zone	FIJCRH	WKZCNT
	Fatal and injury crashes per work zone-hour		WKZHOU
	Fatal and injury crashes per work zone-mile		WKZMIL
	Fatal and injury crashes per work zone-hour-mile		WKHOMI
Fatality and Injury Rates	Fatalities and injuries per work zone	FIJPER	WKZCNT
	Fatalities and injuries per work zone-hour		WKZHOU
	Fatalities and injuries per work zone-mile		WKZMIL
	Fatalities and injuries per work zone-hour-mile		WKHOMI

[a] A rate was calculated by dividing a count measure by an exposure measure. For example, crashes per work zone = ALLCRH ÷ WKZCNT.
[b] Descriptions of the count and exposure measures are provided in Table 2.

Tables 4 through 6 present R^2 values of the estimated regressions where the slope coefficient estimate was statistically significant at the 95th percentile confidence level. An empty cell in the tables indicates that a slope coefficient estimate of a corresponding regression was not statistically significant, meaning it did not meet the linearity condition. Regressions involving hour-related exposures (i.e., work zone-hours and work zone-hour-miles) as an independent variable were statistically significant in general. This means the hour-related exposures had a linear relationship with the count measures (i.e., the linearity condition was satisfied). This further implies that a rate measure employing an hour-related exposure as its denominator is suitable for a safety performance measure of work zones from a statistical standpoint.

For interstate highways (Table 5), estimated regressions involving counts of fatal and injury crashes and crash persons as a dependent variable did not satisfy the linearity condition. This means that a rate using any of these counts as its numerator is not suitable for a safety performance measure for interstate highway work zones. For non-interstate highways (Table 6), rates involving the numbers of work zones and work zone-miles are generally not suitable at the annual level yet are suitable at other temporal levels. This disparity in the results across the different temporal levels is believed to be due in part to the short study data period: 2009-2013.

Table 4. Regression Results for Rate Measures: All Roads

Regression Variables[a]		**R^2**			
Dependent	**Independent**	**Annual**	**Biannual**	**Quarterly**	**Monthly**
ALLCRH	WKZCNT	0.93	0.78		0.60
	WKZHOU	1.00			
	WKZMIL				
	WKHOMI	0.96			
ALLPER	WKZCNT	0.94	0.80		0.62
	WKZHOU	1.00			
	WKZMIL				
	WKHOMI	0.96			
FIJCRH	WKZCNT		0.76	0.75	0.66
	WKZHOU	0.94			
	WKZMIL				
	WKHOMI				
FIJPER	WKZCNT		0.80	0.79	0.63
	WKZHOU	0.98			
	WKZMIL				
	WKHOMI	0.88			

An empty cell indicates that a corresponding regression was not statistically significant in the slope coefficient estimate at the 95th percentile confidence level.
[a] Definitions of variables are provided in Table 2.

Table 5. Regression Results for Rate Measures: Interstate Highways

Regression Variables[a]		R^2			
Dependent	**Independent**	**Annual**	**Biannual**	**Quarterly**	**Monthly**
ALLCRH	WKZCNT	0.89			
	WKZHOU	0.96			
	WKZMIL				
	WKHOMI	0.95			
ALLPER	WKZCNT	0.92			
	WKZHOU	0.97			
	WKZMIL				
	WKHOMI	0.95			
FIJCRH	WKZCNT				0.48
	WKZHOU				
	WKZMIL				
	WKHOMI				
FIJPER	WKZCNT				
	WKZHOU				
	WKZMIL				
	WKHOMI				

An empty cell indicates that a corresponding regression was not statistically significant in the slope coefficient estimate at the 95th percentile confidence level.
[a] Definitions of variables are provided in Table 2.

Table 6. Regression Results for Rate Measures: Non-Interstate Highways

Regression Variables[a]		R^2			
Dependent	**Independent**	**Annual**	**Biannual**	**Quarterly**	**Monthly**
ALLCRH	WKZCNT		0.70		0.63
	WKZHOU	0.95			
	WKZMIL				
	WKHOMI	0.96			
ALLPER	WKZCNT		0.70	0.72	0.65
	WKZHOU	0.94			
	WKZMIL				
	WKHOMI	0.94			
FIJCRH	WKZCNT		0.70	0.79	0.68
	WKZHOU	0.89			
	WKZMIL		0.68	0.75	0.66
	WKHOMI	0.91			
FIJPER	WKZCNT		0.75	0.80	0.67
	WKZHOU	0.95			
	WKZMIL		0.73	0.74	0.63
	WKHOMI	0.96			

An empty cell indicates that a corresponding regression was not statistically significant in the slope coefficient estimate at the 95th percentile confidence level.
[a] Definitions of variables are provided in Table 2.

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, and a threshold index value for a rate to be suitable was fixed at 5.0. The suitability index is calculated as follows:

$$Suitability\ \ Index = 5.0 \times I(Annual) + 4.0 \times I(Biannual)$$
$$+3.0 \times I(Quarterly) + 1.0 \times I(Monthly)$$

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; 5.0, 4.0, … , 1.0 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 5.0 was chosen to disqualify a rate with corresponding regressions being statistically significant only at the quarterly and/or monthly level; thus, regressions that are not statistically significant for both annual and biannual data were excluded from consideration. With the suitability index and its threshold offset at 5.0, a rate is determined to be suitable even when its corresponding regression is 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 5.0, 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 4.0, failing to meet the threshold.

Table 7 shows the 16 rates with the indication of being suitable based on the calculated suitability index values and the threshold. 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, 7 total crash or person rates were suitable but no fatal and injury rates were suitable. For non-interstate highways, 14 rates were suitable excluding 2 rates involving work zone-miles. It should be noted that the suitable rate measures shown in the table are based solely on statistical test results and that practical perspectives should also be considered in conjunction with the statistical results when final performance measures are recommended for Virginia.

Figures 12 through 19 show calculated annual values of 4 crash rates and 4 fatal and injury crash rates. When work zones and work zone-hours were used to calculate a crash rate, except for 2009, non-interstate highways appeared safer than interstate highways in terms of a crash rate per work zone; in Figures 12, 13, 16, and 17, lines for interstate highways are above those for non-interstate highways. However, when work zone-miles and work zone-hour-miles were reflected in the rates, the patterns reversed meaning such that interstate highways appeared safer than non-interstate highways.

Table 7. Suitable Rate Measures Based on Regression Analysis

Rate Measures		All Roads	Interstate Highways	Non-Interstate Highways
Crash Rates	Crashes per work zone	O	O	O
	Crashes per work zone-hour	O	O	O
	Crashes per work zone-mile	X	X	X
	Crashes per work zone-hour-mile	O	O	O
Person Rates	Persons per work zone	O	O	O
	Persons per work zone-hour	O	O	O
	Persons per work zone-mile	X	O	X
	Persons per work zone-hour-mile	O	O	O
Fatal and Injury Crash Rates	Fatal and injury crashes per work zone	O	X	O
	Fatal and injury crashes per work zone-hour	O	X	O
	Fatal and injury crashes per work zone-mile	X	X	O
	Fatal and injury crashes per work zone-hour-mile	X	X	O
Fatality and Injury Rates	Fatalities and injuries per work zone	O	X	O
	Fatalities and injuries per work zone-hour	O	X	O
	Fatalities and injuries per work zone-mile	X	X	O
	Fatalities and injuries per work zone-hour-mile	O	X	O

O = suitable; X = not suitable.

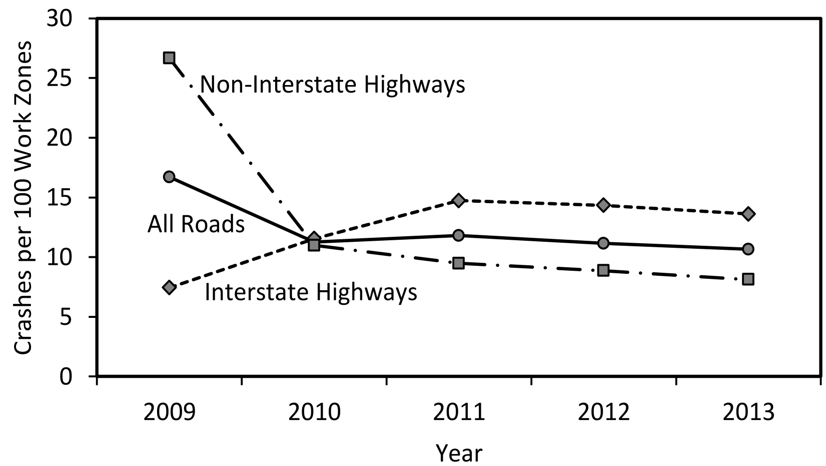


Figure 12. Annual Number of Crashes per 100 Work Zones

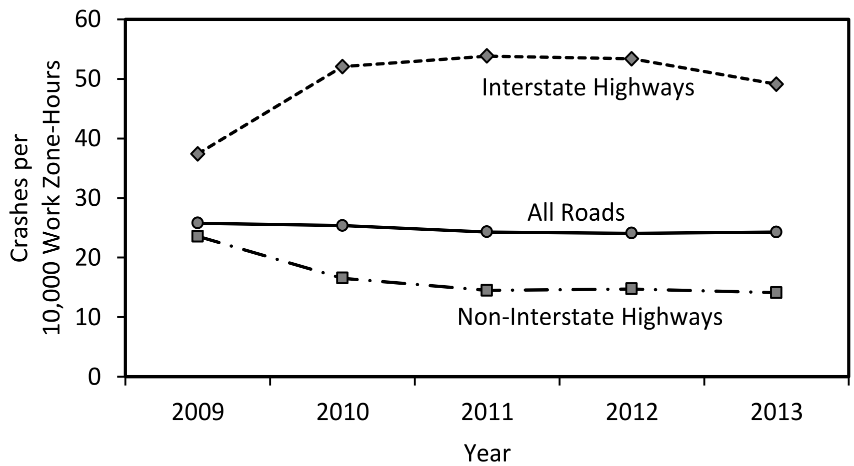


Figure 13. Annual Number of Crashes per 10,000 Work Zone-Hours

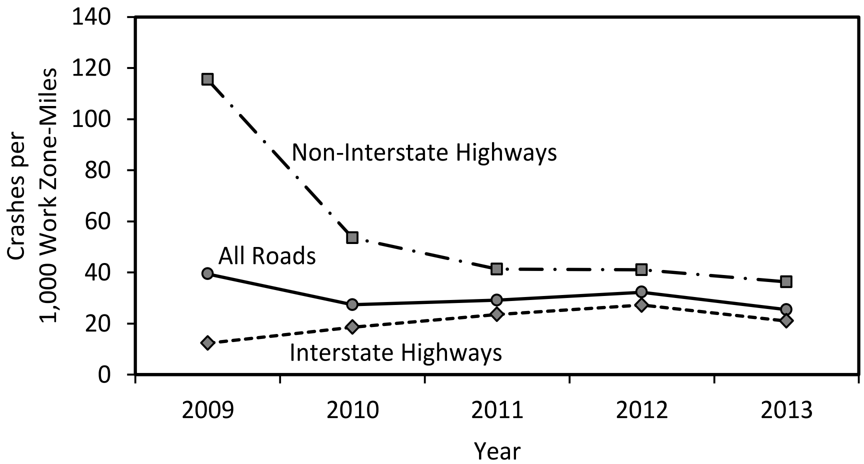


Figure 14. Annual Number of Crashes per 1,000 Work Zone-Miles

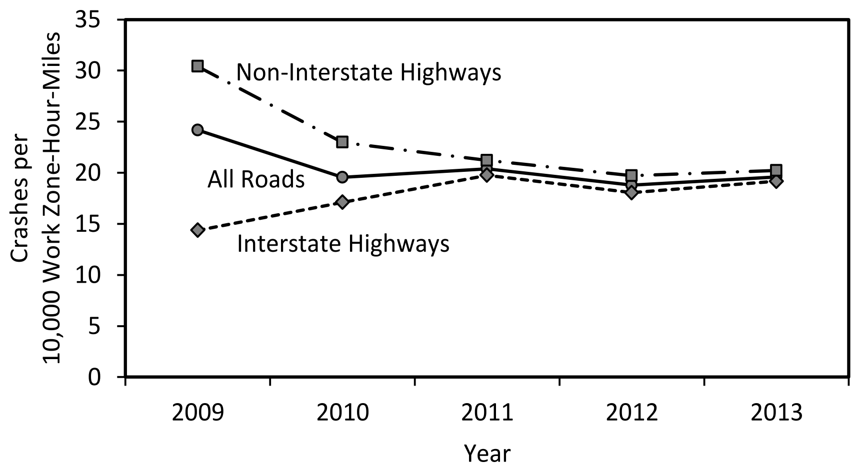


Figure 15. Annual Number of Crashes per 10,000 Work Zone-Hour-Miles

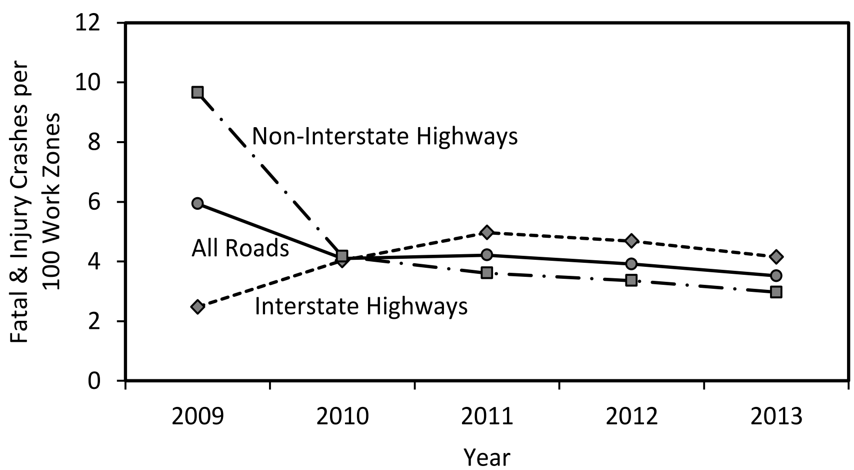


Figure 16. Annual Number of Fatal and Injury Crashes per 100 Work Zones

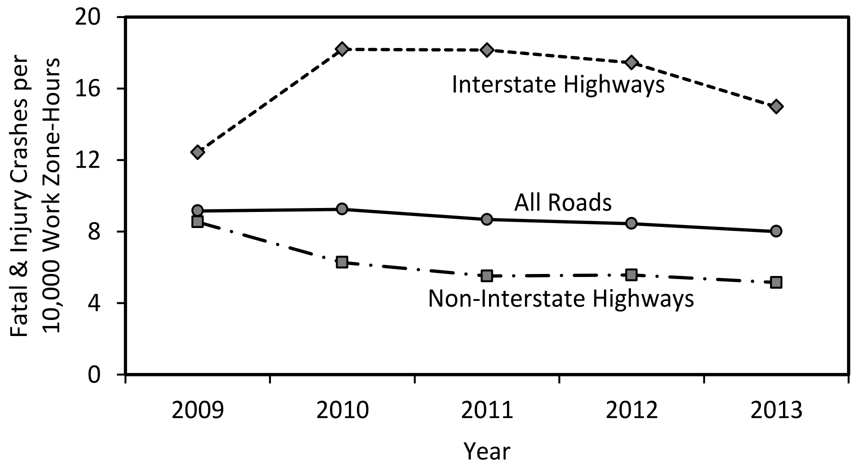


Figure 17. Annual Number of Fatal and Injury Crashes per 10,000 Work Zone-Hours

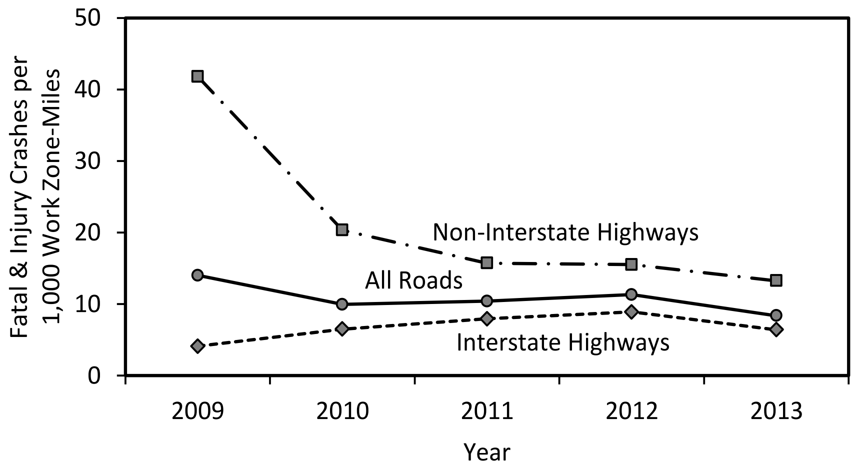


Figure 18. Annual Number of Fatal and Injury Crashes per 1,000 Work Zone-Miles

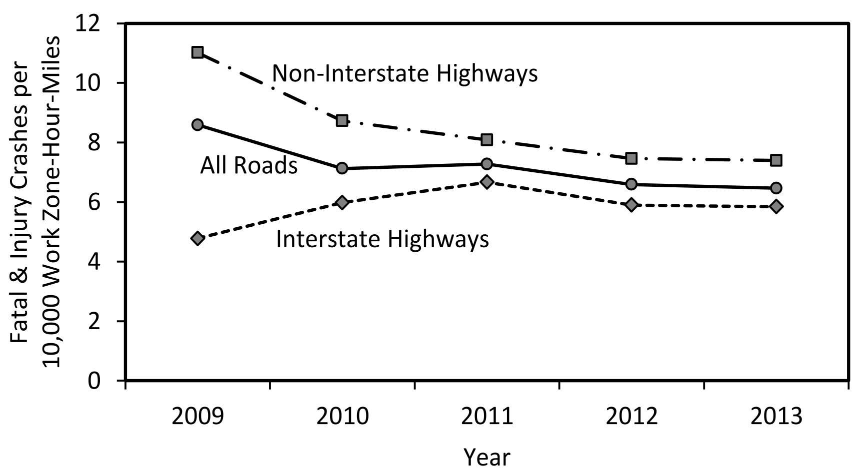


Figure 19. Annual Number of Fatal and Injury Crashes per 10,000 Work Zone-Hour-Miles

As discussed earlier, exposure in terms of work zone-hour-miles is, in theory, superior to the other three exposures in that it reflects an exposure accounting for all three elements of work zones: number, duration, and length. Moreover, the analysis results revealed that the exposure measures accounting for work zone-hours are linearly related to count measures in general. Thus, rates based on work zone-hour-miles would be the best among the rate measures considered in this study. According to the crash rate and the fatal and injury crash rate based on work zone-hour-miles (Figures 15 and 19), interstate highways appeared safer than non-interstate highways. This makes intuitive sense. Further, the rates for non-interstate highways appeared to have decreased continually over the years, meaning that work zone safety for non-interstate highways has been steadily improving.

In order to monitor trends over time, either a crash rate or a fatal crash rate would be sufficient since the trends of these two rates look similar. However, both rates are desired as performance measures so that overall and severity aspects of crash rates are reflected. The difference between the interstate and non-interstate highways is smaller for the total crash rate (e.g., Figure 15) than for the fatal and injury crash rate (e.g., Figure 19). For example, the fatal and injury crash rate for the non-interstate highways was higher on average than that for the interstate highways by 46% whereas the crash rate for the non-interstate highways was higher by 29%.

Recommendations for Work Zone Safety Performance Measures for Virginia

Final safety measures for work zones in Virginia should be determined based not only on statistical tests but also on practical considerations. The study's technical review panel (TRP) reviewed the potential performance measures examined in this study, and input was sought through two rounds of review and discussion. The TRP's inputs on useful performance measures of work zone safety were combined with the evaluation results based on the statistical tests. Based on the combined evaluations, two sets of measures were recommended: performance measures and summary measures. The performance measures represent the statewide safety performance of Virginia's work zones, and the summary measures, although unsuitable for serving as performance measures, still provide useful information regarding work zone safety in Virginia. The performance measures will also be calculated at the district or region level.

Table 8 presents the final recommendations on selected measures of work zone safety in Virginia based on the results of the data analyses and TRP input. Four performance measures and eight summary measures were recommended. The four performance measures were (1) crash count, (2) fatal and injury crash count, (3) crashes per work zone-hour-mile, and (4) fatal and injury crashes per work zone-hour-mile. Measures involving person counts such as crash person count and fatal and injury persons per work zone were not recommended for performance measures partly because of the variability in the number of occupants in a vehicle involved in a traffic crash. All exposure measures were recommended as summary measures but not as performance measures because they provide useful information but are not suitable for setting goals/targets for work zone safety. Appendix C presents calculated annual values of the recommended performance and summary measures by road type, and Appendix D describes a 19-step procedure for preparing data and calculating these measures using VDOT's database.

Table 8. Recommended Measures of Work Zone Safety in Virginia

	Measures of Work Zone Safety	Type
Recommended for Performance Measures		
1	Total Crashes	Count Measure
2	Fatal and Injury Crashes	
3	Crashes per Work Zone-Hour-Mile	Rate Measure
4	Fatal and Injury Crashes per Work Zone-Hour-Mile	
Recommended for Summary Measures		
1	Fatal and Injury Crash Victims	Count Measure
2	Work Zones	Exposure Measure
3	Work Zone-Hours	
4	Work Zone-Miles	
5	Work Zone-Hour-Miles	
6	Crashes per Work Zone	Rate Measure
7	Crashes per Work Zone-Hour	
8	Fatal and Injury Crashes per Work Zone	
Not Recommended for Performance or Summary Measures		
1	Total Crash Victims	Count Measure
2	Fatal and Injury Crashes per Work Zone-Hour	Rate Measure
3	Fatal and Injury Crashes per Work Zone-Mile	
4	Fatal and Injury Victims per Work Zone	
5	Fatal and Injury Victims per Work Zone-Hour-Mile	

It is important to emphasize that these are the recommended performance measures based on currently available data systems and the quality of the data contained therein. Practitioners indicated a desire to develop crash rates based on crashes per VMT. That metric would better account for the level of risk on different facilities. Current work zone data in VaTraffic do not support this measure, however. As data systems improve and work zone activities are logged better, improved crash rate metrics may be possible in the future.

CONCLUSIONS

- *With currently available data, four performance measures are appropriate for monitoring and evaluating the statewide safety performance of work zones and eight summary measures are appropriate for obtaining further insights and understanding with regard to statewide safety issues at work zones in Virginia.* The four performance measures and eight summary measures of work zone safety are listed in Table 8. These measures were selected using the results of statistical analyses and input from the TRP consisting of work zone coordinators and traffic engineers.

- *Exposure measures play a crucial role in assessing the safety performance of work zones in Virginia.* When different road types are compared, count measures (e.g., numbers of crashes and persons) show that non-interstate highways appear safer than or as safe as interstate highways (Figures 4 and 6). However, when exposure measures (e.g., number of work zone-hour-miles) are incorporated, interstate highways appear safer than non-interstate highways (Figures 15 and 19).

- *Exposure measures reflecting both duration and length of work zones are desirable.* Non-interstate highways have a much higher exposure than interstate highways based on work zone-hours (Figure 9), but the opposite is true based on work zone-miles (Figure 10). When work zone-miles and work zone-hours are combined, interstate highways have somewhat higher exposures (Figure 11).

- *There are inconsistencies in the work zone exposure data logged in VaTraffic that directly impact the performance measures determined.* Although performance measures can be generated that are internally consistent, there are likely biases in the data that have a direct impact on the magnitude of exposure measures. This limits the performance measures that can be created and could also create issues related to the comparability of performance measures over time if processes and procedures for logging work zone events in VaTraffic were to change. Because such comparability issues would also exist across different geographic areas, the performance measures are not appropriate for comparing safety performance across regions or districts.

RECOMMENDATIONS

1. *VDOT's Traffic Engineering Division (TED) should use the recommended performance and summary measures of work zone safety for managing the statewide work zone safety program in Virginia.* The four performance measures should be used in monitoring and evaluating the statewide safety performance of work zones. The eight summary measures should be used when additional insights and understanding with regard to statewide safety issues at work zones are desired. At this point, this recommendation applies only to the HSIP annual report and Work Zone Process Review Reports. As TED and the VDOT regions become more familiar and comfortable with the new performance measures, the performance measures may be reported on VDOT's external Dashboard website (VDOT, 2007) if the VDOT Business Transformation Office agrees. District-specific measures can be used for further understanding of work zone safety issues but because of comparability issues should not be used for comparing safety performance across districts. However, there would be ways of using them for such a purpose. For example, a ratio or percentage comparing the current measures of a district with its past values can be calculated to indicate how well the district performs in the current year compared to its past performance and used for comparison across districts.

2. *If VaTraffic undergoes changes in its data management processes, database structure, or data entry practices, VDOT's TED should examine the impact of those changes on the recommended safety performance measures*. Because exposure measures are calculated using work zone information extracted from the VaTraffic database, changes in VaTraffic could cause inconsistencies in the performance and summary measures before and after the changes. Likewise, if work zone logging procedures improve, it may be possible to develop improved rate-based measures.

BENEFITS AND IMPLEMENTATION

Benefits

The work zone safety performance measures developed in this study can be used to compare the statewide annual performance of work zone safety in Virginia over time. The performance and summary measures can be used to identify potential areas for improvement in Virginia's work zone safety program, leading to improved work zone safety in Virginia. The measures calculated at the biannual, quarterly, and/or monthly level can provide different, more detailed aspects of work zone safety in Virginia, compared to the annual measures. Statewide, district, and region values of these measures will be calculated by VDOT's TED.

Implementation

Regarding Recommendation 1, upon the annual completion of data gathering regarding work zone crashes for a calendar year, VDOT's TED will use the recommended performance and summary measures in reporting to FHWA through the HSIP report, the Work Zone Process Review Report, and/or the Outside VDOT website (VDOT, 2016). In addition, the TED will annually share the performance measures with regional traffic engineers and their staff for their respective district.

Regarding Recommendation 2, VDOT's TED will continue to monitor VaTraffic on a quarterly basis and work with VDOT's Operations Division and others in providing input to improve the documentation of work zone information in this system.

ACKNOWLEDGMENTS

The authors thank the members of the TRP (David Rush, VDOT's TED; Mark Cole, VDOT's TED; Tim Rawls, formerly Hampton Roads District TED; and Forester Wright, Northwest Region TED) for their guidance and input throughout this study.

REFERENCES

Arkansas Highway Safety Steering Committee. *Arkansas Strategic Highway Safety Plan 2013.* Little Rock, 2013.

Colorado Department of Transportation. *Colorado Strategic Highway Safety Plan.* Denver, 2014.

Federal Highway Administration. *Work Zone Mobility and Safety Self-Assessment Guide.* 2004. http://www.ops.fhwa.dot.gov/wz/docs/wz-sa-docs/sa_guide_s1.htm#sec1. Accessed August 20, 2015.

Governor's Traffic Safety Advisory Commission. *2013-2016 State of Michigan Strategic Highway Safety Plan.* Lansing, 2012.

Governor's Traffic Safety Advisory Council. *Arizona Strategic Highway Safety Plan.* Phoenix, 2007.

Governors Highway Safety Association. *MMUCC Guideline: Model Minimum Uniform Crash Criteria*, Fourth Edition. Washington, DC, 2012.

Indiana Department of Transportation. *Strategic Highway Safety Plan: 2010 Revision.* Indianapolis, 2010.

Iowa Department of Transportation. *Iowa Comprehensive Highway Safety Plan.* Ames, 2006.

Massachusetts Department of Transportation. *Massachusetts Strategic Highway Safety Plan.* Boston, 2013.

Missouri Coalition for Roadway Safety. *Missouri's Blueprint to Save More Lives 2012-2016.* Jefferson, 2012.

New Jersey Department of Transportation. *Comprehensive Strategic Highway Safety Plan.* Trenton, 2007.

New York State Department of Transportation. *2010 New York State Strategic Highway Safety Plan.* Albany, 2010.

North Carolina Department of Transportation. *North Carolina's Strategic Highway Safety Plan*. Raleigh, 2005.

Ohio Department of Transportation. *Ohio Strategic Highway Safety Plan: 2009 Update.* Columbus, 2009.

Oregon Transportation Commission. *2011 Transportation Safety Action Plan.* Salem, 2011.

Pennsylvania Department of Transportation. *Pennsylvania Strategic Highway Safety Plan.* Harrisburg, 2012.

State of Alabama. *Strategic Highway Safety Plan for Alabama*, Second Edition. Montgomery, 2012.

State of California. *California Strategic Highway Safety Plan Version 2*. Sacramento, 2006.

State of Connecticut. *Connecticut Strategic Highway Safety Plan.* Hartford, 2013.

State of Delaware. *Delaware Strategic Highway Safety Plan: Toward Zero Deaths*. Dover, 2010.

State of Florida. *Florida Strategic Highway Safety Plan.* Tallahassee, 2012.

State of Georgia. *2012 Georgia Strategic Highway Safety Plan.* Atlanta, 2012.

State of Illinois. *Illinois Strategic Highway Safety Plan.* Springfield, 2009.

State of Kansas. *Kansas Strategic Highway Safety Plan.* Topeka, 2007.

State of Louisiana. *Louisiana Strategic Highway Safety Plan.* Baton Rouge, 2011.

State of Maryland. *Maryland Strategic Highway Safety Plan 2011-2015.* Annapolis, 2011.

State of Minnesota. *Minnesota Strategic Highway Safety Plan.* Saint Paul, 2007.

State of Tennessee. *State of Tennessee Strategic Highway Safety Plan.* Nashville, 2009.

State of Washington. *Washington State's Strategic Highway Safety Plan 2010*. Olympia, 2010.

Texas Department of Transportation. *2014 Texas Strategic highway Safety Plan.* Austin, 2014.

Ullman, G.L., and Lomax, T.J. *A Primer on Work Zone Safety and Mobility Performance Measurement.* FHWA-HOP-11-033. Federal Highway Administration, Washington, DC, 2011.

Utah Safety Leadership Team. *Utah Comprehensive Safety Plan.* Salt Lake City, 2006.

Virginia Department of Transportation. *1999-2003 Virginia Work Zone Crash Facts.* Richmond, 2006.

Virginia Department of Transportation. Dashboard: Performance Reporting System for Projects and Programs. 2007. http://dashboard.virginiadot.org/. Accessed March 7, 2016.

Virginia Department of Transportation. *FY 2011-12 Annual Report Highway Safety Improvement Program*. Richmond, 2011.

Virginia Department of Transportation. *Virginia 2012-2016 Strategic Highway Safety Plan.* Richmond, 2012.

Virginia Department of Transportation. Outside VDOT. 2016. https://outsidevdot.cov.virginia.gov/_layouts/OutsideVDOT.Authentication.CustomLogin/OvdCustomLogin.aspx?ReturnUrl=%2fP0JQP%2f_layouts%2fAuthenticate.aspx%3fSource%3d%252FP0JQP%252F2007%255FStandard%255FSpecifications%252FForms%252FAF%252Easpx&Source=%2FP0JQP%2F2007%5FStandard%5FSpecifications%2FForms%2FAF%2Easpx. Accessed March 7, 2016.

APPENDIX A

STATE STRATEGIC HIGHWAY SAFETY PLANS

The SHSPs of 30 states were located online and reviewed in the search for practical work zone safety performance measures. Table A1 lists the reviewed plans. Almost all states developed their SHSPs around 2006 in that a SHSP is a requirement of the HSIP (23 U.S.C. § 148), and many of them revised their plans several years later. It should be noted that SHSPs found online, not necessarily the most recent versions of the plans, were reviewed for this study.

Table A1. State Strategic Highway Safety Plans Reviewed

State/Author	Title	Publication Year
Alabama/State of Alabama	Strategic Highway Safety Plan for Alabama, Second Edition	2012
Arizona/Governor's Traffic Safety Advisory Council	Arizona Strategic Highway Safety Plan	2007
Arkansas/Arkansas Highway Safety Steering Committee	Arkansas Strategic Highway Safety Plan 2013	2013
California/State of California	California Strategic Highway Safety Plan Version 2	2006
Colorado/Colorado Department of Transportation	Colorado Strategic Highway Safety Plan	2014
Connecticut/State of Connecticut	Connecticut Strategic Highway Safety Plan	2013
Delaware/State of Delaware	Delaware Strategic Highway Safety Plan: Toward Zero Deaths	2010
Florida/State of Florida	Florida Strategic Highway Safety Plan	2012
Georgia/State of Georgia	2012 Georgia Strategic Highway Safety Plan	2012
Illinois/State of Illinois	Illinois Strategic Highway Safety Plan	2009
Indiana/Indiana Department of Transportation	Strategic Highway Safety Plan: 2010 Revision	2010
Iowa/Iowa Department of Transportation	Iowa Comprehensive Highway Safety Plan	2006
Kansas/State of Kansas	Kansas Strategic Highway Safety Plan	2007
Louisiana/State of Louisiana	Louisiana Strategic Highway Safety Plan	2011
Maryland/State of Maryland	Maryland Strategic Highway Safety Plan 2011-2015	2011
Massachusetts/Massachusetts Department of Transportation	Massachusetts Strategic Highway Safety Plan	2013
Michigan/ Governor's Traffic Safety Advisory Commission	2013-2016 State of Michigan Strategic Highway Safety Plan	2012
Minnesota/State of Minnesota	Minnesota Strategic Highway Safety Plan	2007
Missouri/Missouri Coalition for Roadway Safety	Missouri's Blueprint to Save More Lives 2012-2016	2012
New Jersey/New Jersey Department of Transportation	Comprehensive Strategic Highway Safety Plan	2007
New York/New York State Department of Transportation	2010 New York State Strategic Highway Safety Plan	2010
North Carolina/North Carolina Department of Transportation	North Carolina's Strategic Highway Safety Plan	2005
Ohio/Ohio Department of Transportation	Ohio Strategic Highway Safety Plan: 2009 Update	2009
Oregon/Oregon Transportation Commission	2011 Transportation Safety Action Plan	2011
Pennsylvania/Pennsylvania Department of Transportation	Pennsylvania Strategic Highway Safety Plan	2012
Tennessee/State of Tennessee	State of Tennessee Strategic Highway Safety Plan	2009
Texas/Texas Department of Transportation	2014 Texas Strategic highway Safety Plan	2014
Utah/Utah Safety Leadership Team	Utah Comprehensive Safety Plan	2006
Virginia/Virginia Department of Transportation	Virginia 2012-2016 Strategic Highway Safety Plan	2012
Washington/State of Washington	Washington State's Strategic Highway Safety Plan 2010	2010

APPENDIX B

QUARTERLY COUNT AND EXPOSURE MEASURES

Count Measures

Figures B1 through B4 show four quarterly count measures by road type, corresponding to annual counterparts in Figures 4 through 7 in the body of the report. Unusually high numbers in the third and fourth quarters of 2009 are noticeable.

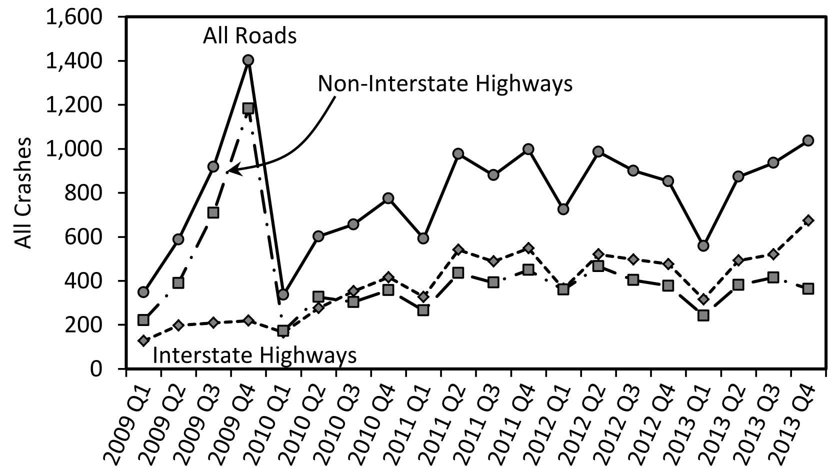


Figure B1. Quarterly Number of All Work Zone Crashes. Note that work zone traffic crashes are counted.

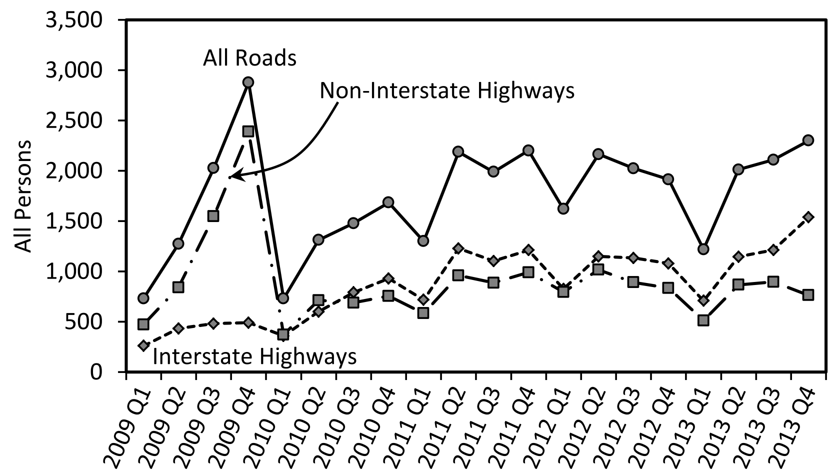


Figure B2. Quarterly Number of All Work Zone Persons. Note that persons involved in a traffic crash including all drivers and injured and fatal non-drivers are counted.

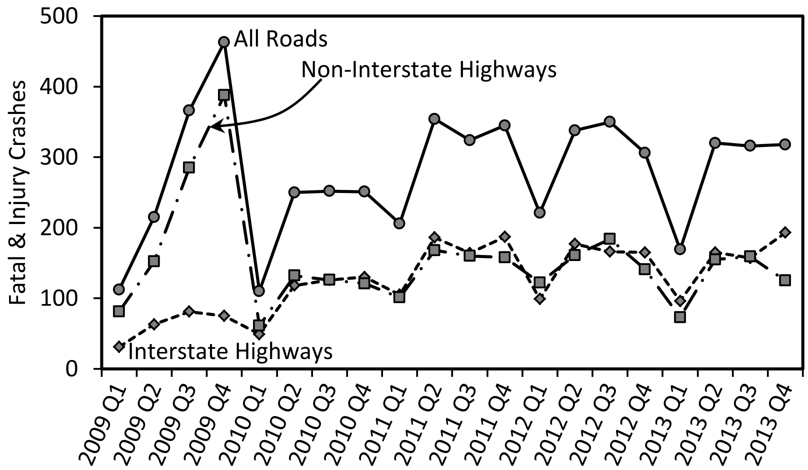


Figure B3. Quarterly Number of Fatal and Injury Work Zone Crashes. Note that work zone traffic crashes resulting in a fatality or injury are counted.

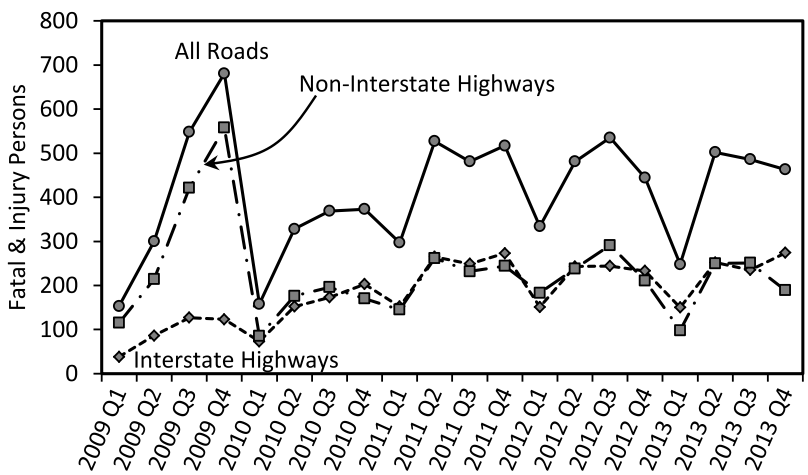


Figure B4. Quarterly Number of Fatal and Injury Persons. Fatal or injured persons in a traffic crash were counted.

Exposure Measures

Figures B5 through B8 show quarterly exposure measures corresponding to annual counterparts in Figures 8 through 11 in the body of the report. Overall, the exposure trends are generally matched with the count trends. However, the unusual spikes of the count measures in the third and fourth quarters of 2009 are not matched with the exposure trends: unusually high numbers of work zone-hour-miles are noted in the second and third quarters of 2009.

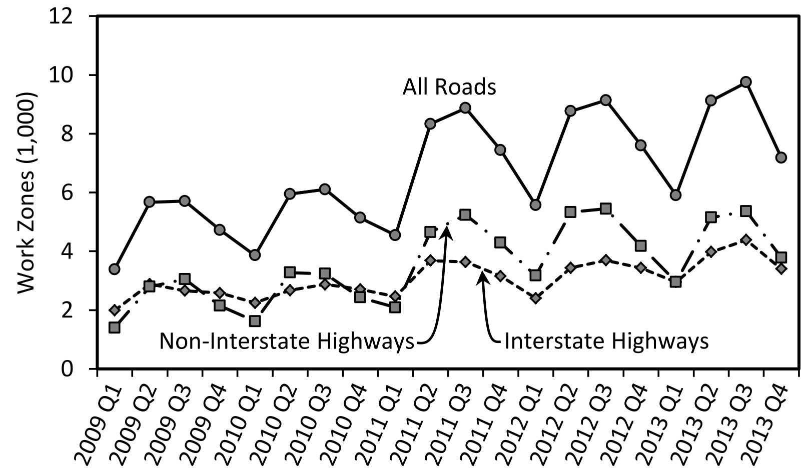


Figure B5. Quarterly Number of Work Zones

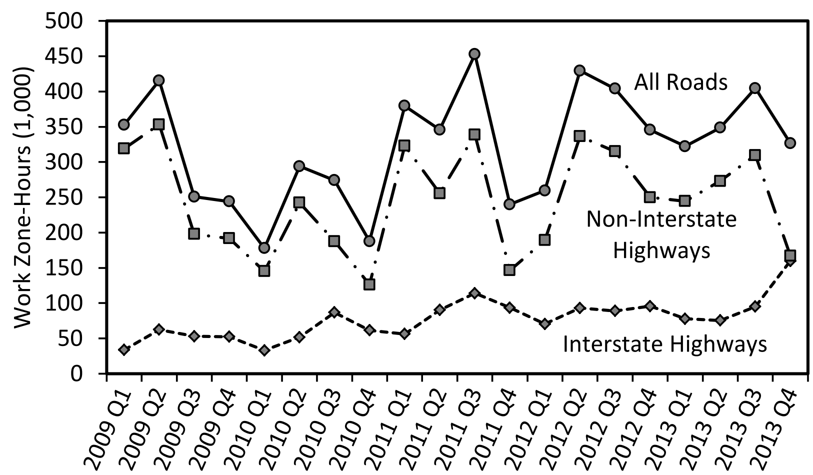


Figure B6. Quarterly Number of Work Zone-Hours

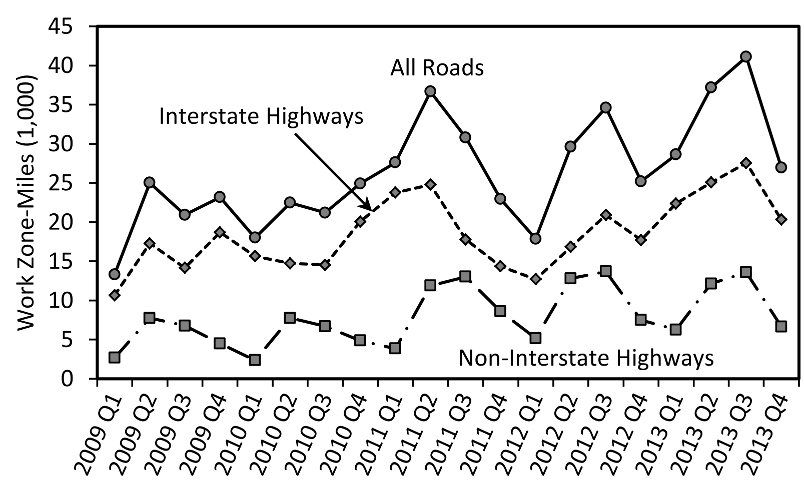


Figure B7. Quarterly Number of Work Zone-Miles

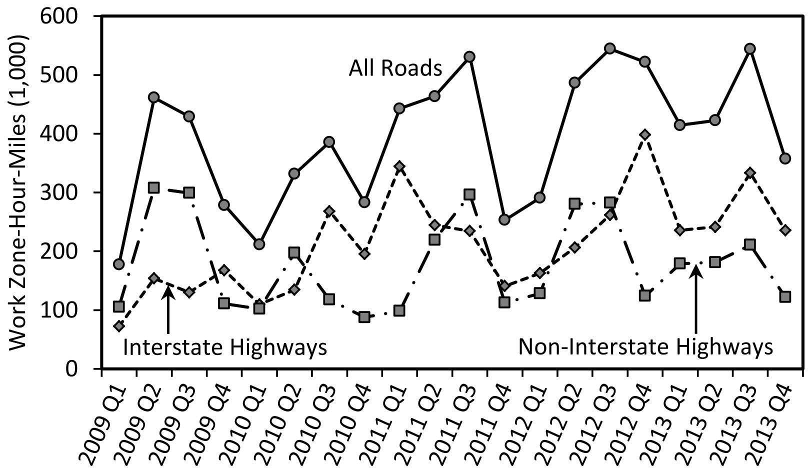


Figure B8. Quarterly Number of Work Zone-Hour-Miles

APPENDIX C

VIRGINIA'S WORK ZONE SAFETY PERFORMANCE AND SUMMARY MEASURES

Overview

The study recommended 4 performance measures and 8 summary measures of work zone safety in Virginia as follows, and a procedure for calculating these measures using VDOT's database is described in Appendix D.

4 Performance Measures (PMs)

- PM1: Total Crashes
- PM2: Fatal and Injury Crashes
- PM3: Crashes per Work Zone-Hour-Mile
- PM4: Fatal and Injury Crashes per Work Zone-Hour-Mile.

8 Summary Measures (SMs)

- SM1: Fatal and Injury Crash Victims
- SM2: Work Zones
- SM3: Work Zone-Hours
- SM4: Work Zone-Miles
- SM5: Work Zone-Hour-Miles
- SM6: Crashes per Work Zone
- SM7: Crashes per Work Zone-Hour
- SM8: Fatal and Injury Crashes per Work Zone.

These measures calculated using 2009-2013 data are presented in Figures C1 through C12. For these measures, the following should be noted:

- A *work zone crash* is defined as a traffic crash reported to the police with an indication of "active work zone" on the police crash report.

- To calculate a work zone crash exposure, a *work zone* is defined as an event being indicated as "work zone" with the same event ID in VaTraffic. This definition of a *work zone* is used in calculating 2 performance measures (PM3 and PM4) and 7 summary measures (SM2 through SM8).

Performance Measures

Four performance measures of work zone safety (PM1 through PM4) are presented here.

PM1: Total Crashes

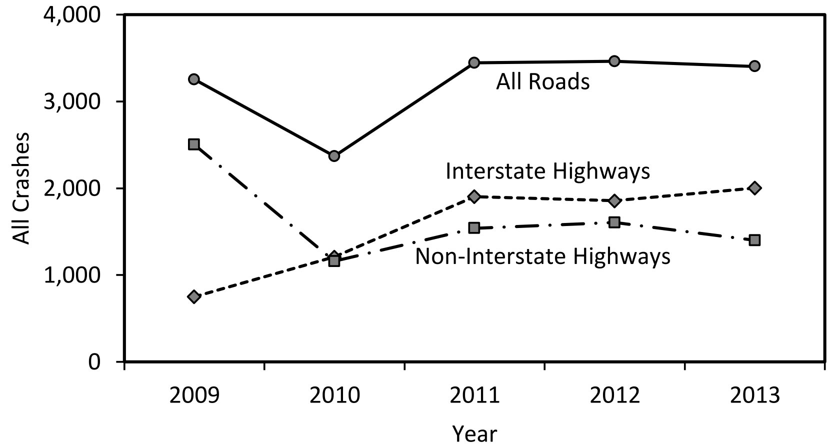


Figure C1. Total Work Zone Crashes in Virginia

PM2: Fatal and Injury Crashes

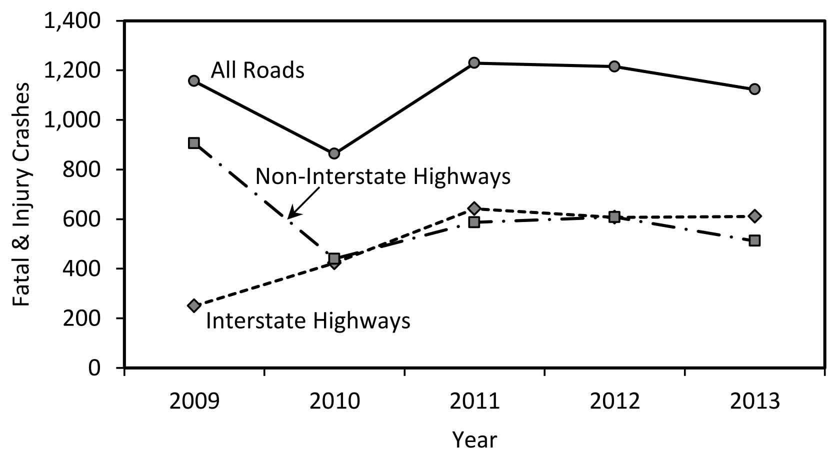


Figure C2. Fatal and Injury Work Zone Crashes in Virginia

PM3: Crashes per Work Zone-Hour-Mile

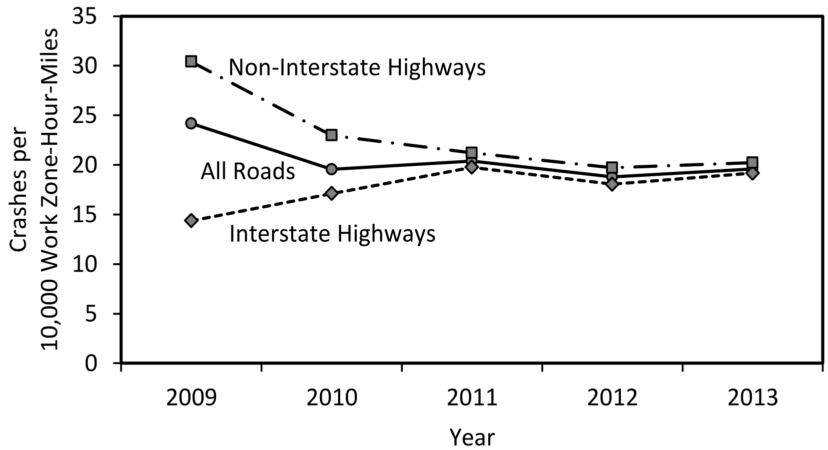


Figure C3. Total Crashes per 10,000 Work Zone-Hour-Miles in Virginia

PM4: Fatal and Injury Crashes per Work Zone-Hour-Mile

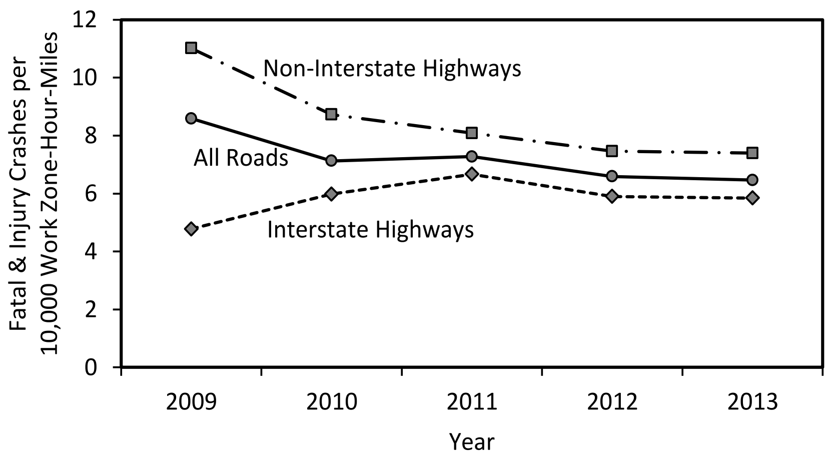


Figure C4. Fatal and Injury Crashes per 10,000 Work Zone-Hour-Miles in Virginia

Summary Measures

Eight summary measures of work zone safety are presented here.

SM1: Fatal and Injury Crash Victims

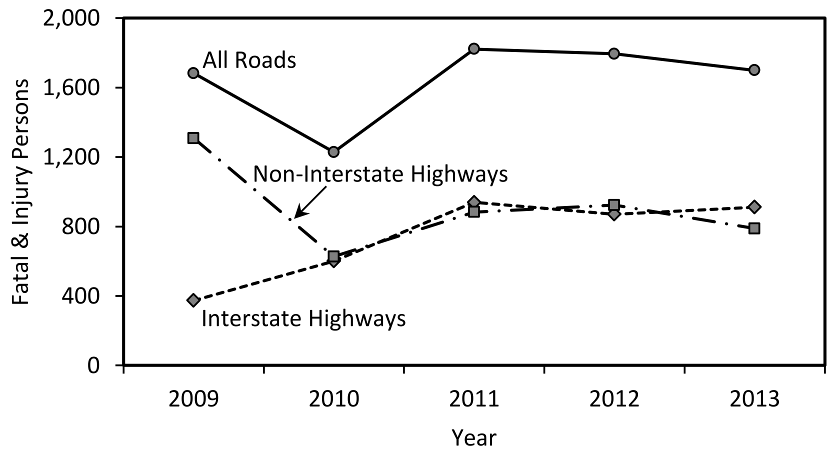


Figure C5. Fatal and Injury Persons in Work Zone Crashes in Virginia

SM2: Work Zones

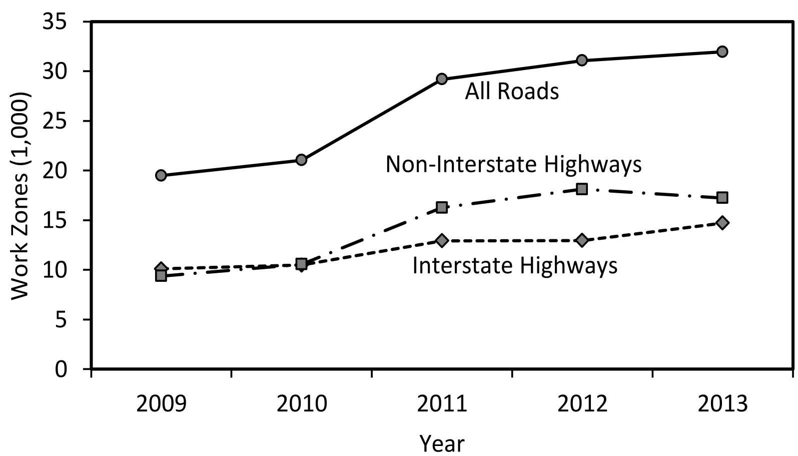


Figure C6. Work Zones in Virginia

SM3: Work Zone-Hours

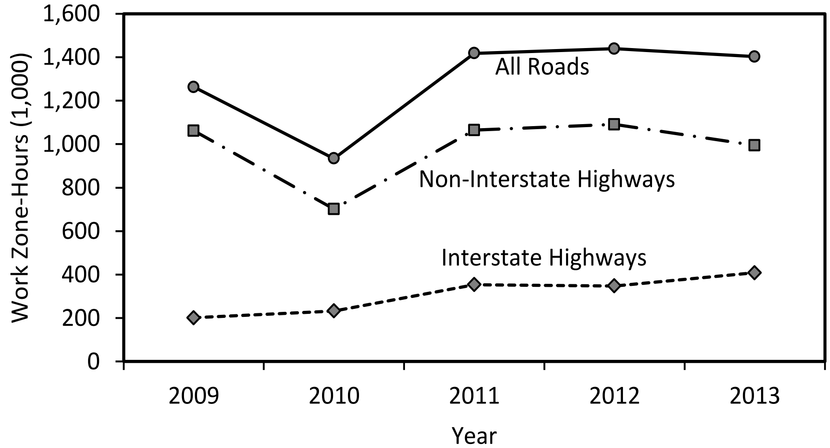


Figure C7. Work Zone-Hours in Virginia

SM4: Work Zone-Miles

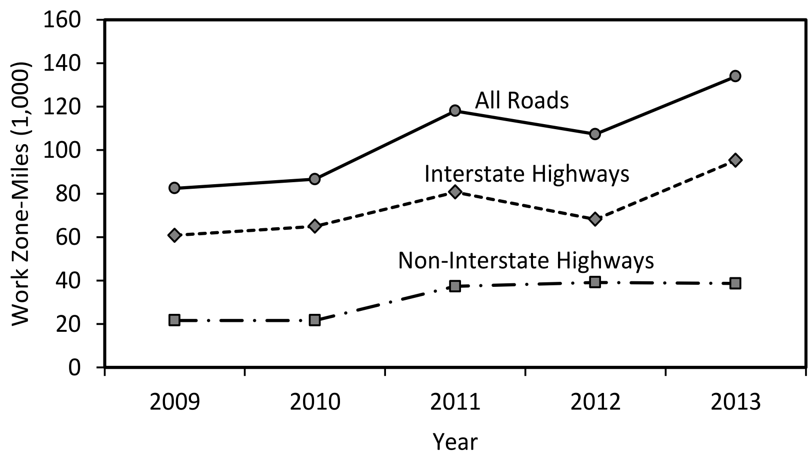


Figure C8. Work Zone-Miles in Virginia

SM5: Work Zone-Hour-Miles

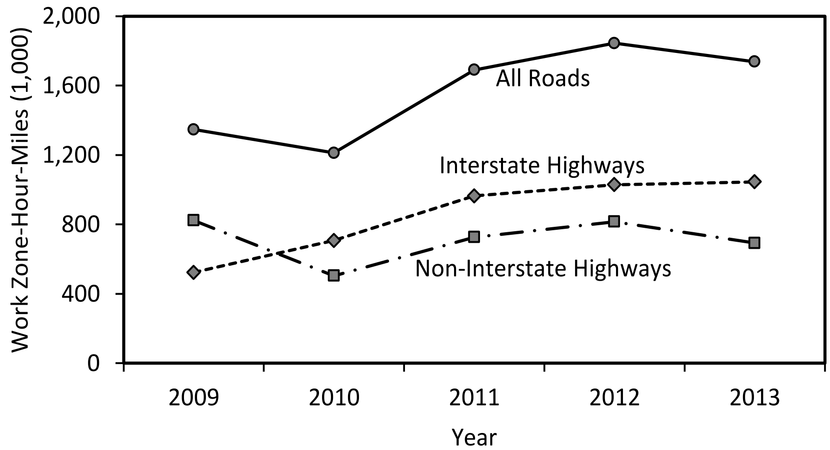


Figure C9. Work Zone-Hour-Miles in Virginia

SM6: Crashes per Work Zone

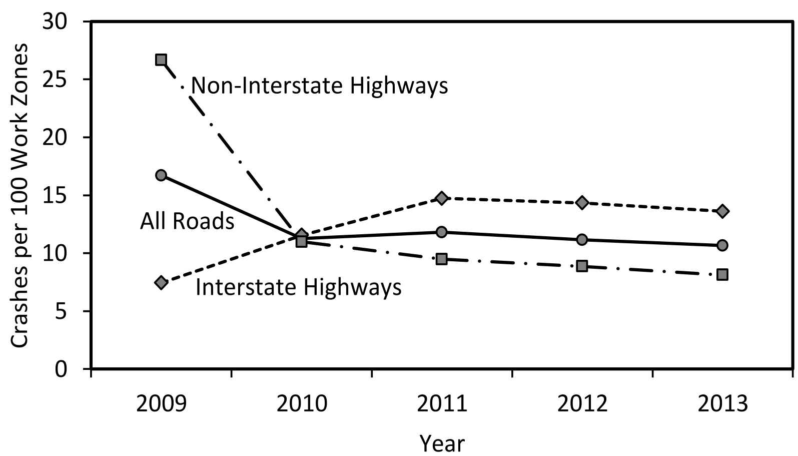


Figure C10. Total Crashes per 100 Work Zones in Virginia

SM7: Crashes per Work Zone-Hour

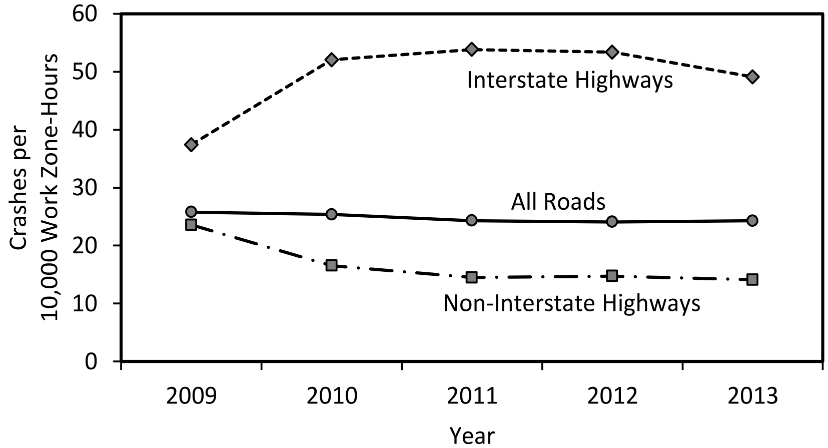


Figure C11. Total Crashes per 10,000 Work Zone-Hours in Virginia

SM8: Fatal and Injury Crashes per Work Zone

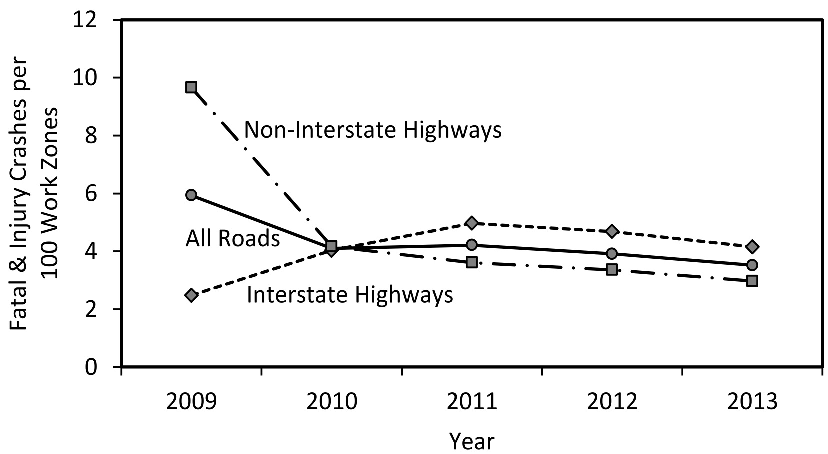


Figure C12. Fatal and Injury Crashes per 100 Work Zones in Virginia

APPENDIX D

PROCEDURE OF CALCULATING MEASURES OF WORK ZONE SAFETY

Count, exposure, and rate measures of work zone safety performance are obtained in a 19-step procedure described here and shown in Figure D1. STEPs 1 through 8 are performed while connecting the RNS database, and STEPs 10 through 17 are performed while connecting the VaTraffic database. STEPs 9, 18, and 19 are performed without connecting to the database. This procedure is executed for 1 year of interest for all roads in Virginia so that calculated measures are for Virginia in that year. However, it can also be executed by district or region and/or by different time units such as quarter or month with some modifications. To calculate measures separately for interstate highways and non-interstate highways, an accordant selection step should be added for "Calculation of Count Measures and Calculation of Exposure Measures."

Calculation of Count Measures

STEP 1 Connect RNS database.

STEP 2 Access to RNS_CRASH subsystem.

STEP 3 Open RNS_CRASH.TBL_CRASH table.

STEP 4 Select work zone crashes: WORK_ZONE_RELATED_CD=1.

STEP 5 Store the records selected at STEP 4 in a view.

STEP 6 Join the following three tables by CRASH_ID field as a primary key and create a crash severity field following KABCO scale using three person's injury severity fields stated in the parenthesis:

- RNS_CRASH.TBL_VEHICLE_DRIVER table (DRIVER_INJURY_TYPE_CD field)
- RNS_CRASH.TBL_VEHICLE_PASSENGER table (PASSENGER_INJURY_TYPE_CD field)
- RNS_CRASH.TBL_PEDESTRIAN table (PED_INJURY_TEYP_CD field).

STEP 7 Join the crash severity field created at STEP 6 to the view created at STEP 5 by CRASH_ID field as a primary key.

STEP 8 Now, the view has KABCO scale crash severity information for each work zone crash record.

STEP 9 Calculate the following aggregate counts:

- Crash: Count crashes
- Fatal and Injury Crash: Count fatal and injury crashes
- Fatal and Injury Victim: Count fatal and injury persons.

Calculation of Exposure Measures

STEP 10 Connect VaTraffic database.

STEP 11 Access to ORCIDEV_DBA subsystem.

STEP 12 Open ORCIDEV_DBA.EVENT_MASTER table.

STEP 13 Join the following two tables containing detailed event plan and location information by EVENT_ID field as a primary key:

- ORCIDEV_DBA.EVENT_PLANNED table
- ORCIDEV_DBA.EVENT_LOCATION_SEGMENT table.

STEP 14 Join table joined at STEP 13 to ORCIDEV_DBA.EVENT_MASTER by EVENT_ID field as a primary key.

STEP 15 Select only work zone events defined with EVENT_TYPE_CD=4.

Note that adding SUBSTR(ROUTE_NM, 1, 2)='I-' to the selection condition will select work zone events on interstate highways; unselected events will be those for non-interstate highways.

STEP 16 Store records selected at STEP 15 in a view.

STEP 17 Create the following three fields:

- WZ_Hour: Subtract START_DT field from END_DT field
- WZ_Mile: Subtract START_MILEMARKER_NBR field from END_MILEMARKER_NBR field
- WZ_Hour_Mile: Multiply WZ_Hour field and WZ_Mile field.

STEP 18 Calculate the following aggregate exposures:

- Work Zone: Count unique EVENT_IDs
- Work Zone-Hour: Summate WZ_Hour field by EVENT_ID field, then summate summed WZ_Hour over all EVENT_IDs
- Work Zone-Mile: Summate WZ_Mile field by EVENT_ID field, then summate summed WZ_Mile over all EVENT_IDs

- Work Zone-Hour-Mile: Summate WZ_Hour_Mile field by EVENT_ID field, then summate summed WZ_Hour_Mile over all EVENT_IDs

Calculation of Rate Measures

STEP 19 Calculate the following rate measures using aggregate counts produced at STEP 9 and aggregate exposures produced at STEP 18:

- Crashes per Work Zone: Divide Crash from STEP 9 by Work Zone from STEP 18
- Crashes per Work Zone-Hour: Divide Crash from STEP 9 by Work Zone-Hour from STEP 18
- Crashes per Work Zone-Hour-Mile: Divide Crash from STEP 9 by Work Zone-Hour-Mile from STEP 18
- Fatal and Injury Crashes per Work Zone: Divide Fatal and Injury Crash from STEP 9 by Work Zone from STEP 18
- Fatal and Injury Crashes per Work Zone-Hour-Mile: Divide Fatal and Injury Crash from STEP 9 by Work Zone-Hour-Mile from STEP 18

Note: Rate measures other than these can be calculated using outcomes produced from STEPs 1 through 18. For example, “Fatal and Injury Victims per Work Zone” can be calculated by dividing “Fatal and Injury Victim” from STEP 9 by “Work Zone” from STEP 18.

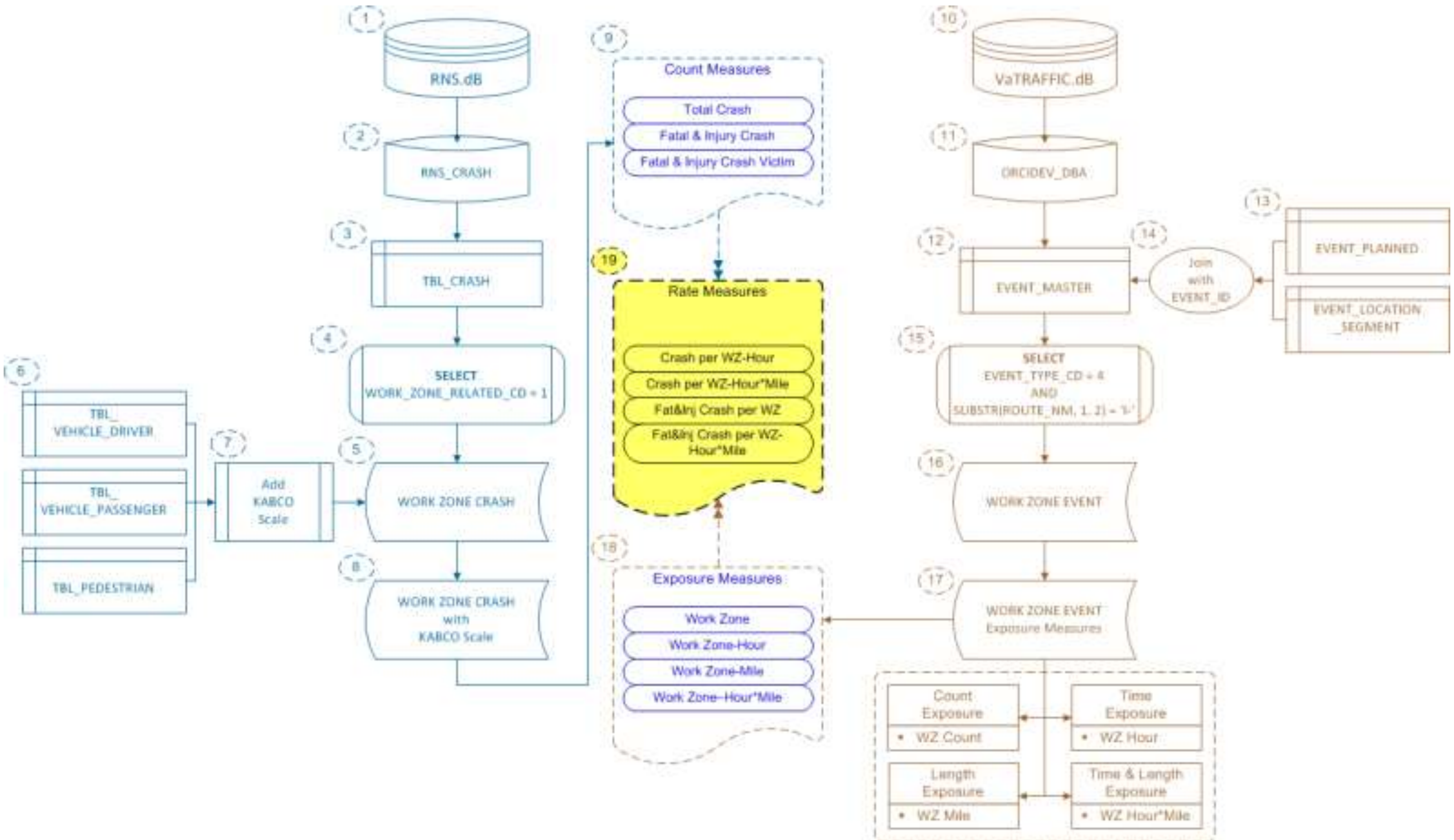


Figure D1. A Procedure of Calculating Measures of Work Zone Safety. Note that this procedure is executed for a year of interest for all roads in Virginia so that calculated measures are for Virginia in that year.