Integrating Crash, Real-time Traffic and Lane Closure Data for Statewide Highway Work Zone Safety Analysis

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Abstract

Research indicates that highway work zones interrupt regular traffic flow and increase crash risks. Work zone safety analysis can help identify the risk factors and improve work zone safety. Ideally, a variety of data sources including crash reports, work zone attributes, and traffic detection are needed to support work zone safety analysis. However, the data is usually very limited in terms of quantity, quality and completeness, especially for traffic data. Most existing studies have to rely on estimated average daily traffic (ADT) because actual traffic data is unavailable. This paper integrates actual work zone traffic data from traffic detectors, police crash reports and statewide lane closure records and calculates the crash rates and crash costs by the actual vehicle miles traveled (VMT) for several work zone attribute categories. The results provide a comprehensive and systematic review of statewide work zone safety. The key to this integration is the successful alignment of previously disparate data sources to a common linear referencing system, and the general ideas can also be applied to other similar traffic related data systems.
INTRODUCTION

Many studies (1-4) demonstrated the connection between the presence of work zones and the safety risk to travelers and workers. Work zone safety analysis can help identify the risk factors and improve work zone safety. Effective safety analysis requires consideration of a variety of data sources, including detailed information about crashes in and around a work zone, driver and environmental factors, and work zone attributes. However, the data available and ready to use is usually limited in terms of quantity and completeness. The traditional approach has relied on the police crash reports to identify work zone crashes and obtain information about them. Although the police crash reports provide details about crashes, they do not include details about the work zones, except when noted in the officer’s narrative descriptions. Targeted work zone studies provide a wealth of information for specific work zones, but they are limited in number and scope because of the high costs of data collection.

There are many studies about modeling work zone crash rates regarding work zone, driver and environment attributes using a variety of statistical methods to investigate (3, 5-7). It is recognized that crash rates based on “the exposure to the risk” (8, 9) provides the fundamentals to help safety researchers assess work zone safety and develop countermeasures, while absolute crash frequencies cannot provide such insights. In general, the number of work zone crashes increase with work zone duration, length and volume, which are usually considered when developing the crash rate, even if not used directly. However, the work zone begin and end locations, the start and end dates, are usually not well recorded (10). Since the actual traffic flow volume is often unavailable, most studies have to use average daily traffic (ADT) to estimate the actual traffic volume going through the work zone, which is considered to cause significant bias (4, 11, 12). Therefore, in addition to the limited data availability, data accuracy issues cause difficulties in work zone crash studies as well.

With the help of modern transportation information systems, we are able to manage and archive significant amounts of transportation related data. However, these information systems are often oriented towards specific purposes and different application areas; the data pulled from them are usually in different formats and by different standards (13). Ideally, work zone crash analysis would involve several categories of information, such as work zone planning and management, traffic data, and work zone crash records. It is necessary to develop ways to integrate data across these systems. This study is an attempt to integrate statewide lane closure data, police crash reports, and ITS traffic detector data, in order to provide a comprehensive data foundation to work zone crash analysis. The underlying data integration method is based on the WisDOT State Trunk Network (STN) linear referencing system, which provides a common geospatial information system (GIS) network of state-maintained highways for these different data sets. A preliminary analysis of highway work zone safety based on the Wisconsin Lane Closure System (WisLCS) closure attributes is presented.

This paper is organized as follows. The data sources used in this study are introduced. A data integration method is proposed to correlate work zones with traffic detectors and crashes. While the work zone length and duration can be easily calculated based on work
zone records, a method is introduced to obtain the actual vehicle miles traveled (VMT) for individual work zones. The key to this integration is the successful alignment of previously disparate data sources to a common linear referencing system. Based on the aforementioned exposure data, work zone crash rates for different groups of work zone attributes are calculated.

**DATA SOURCES**

The Traffic Operations and Safety (TOPS) Laboratory at the University of Wisconsin-Madison has developed three systems through collaboration with the Wisconsin Department of Transportation (WisDOT) which provide the data used in this study: the Wisconsin Lane Closure System (WisLCS) (14), the Wisconsin MV4000 crash database (15), and the Wisconsin VSPOC (Volume, Speed, and Occupancy) Traffic Detector Archived Data Management System (16). These systems are available through the WisTransPortal (17) platform.

**The Wisconsin Lane Closure System (WisLCS)**

Operational since April 2008, the WisLCS provides a centralized acceptance and reporting system for highway lane closures and restrictions statewide. The WisLCS streamlines the work zone operation and scheduling decisions and provides better information to 511, Oversize/Overweight (OSOW) truck permitting and related real time systems (18). All highway closures and restrictions are entered into the WisLCS prior to the closure start-date. Updates to closure schedules and other details are also entered into the system in near real-time. As such, the WisLCS provides a comprehensive, highly accurate database of statewide highway lane closures in Wisconsin. Lane closure records in the WisLCS are automatically geo-located as they are entered into the system.

**Wisconsin MV4000 Crash Data**

The WisTransPortal Crash Data Retrieval Facility (15) provides access to Wisconsin MV4000 Traffic Accident Extract data from 1994 through the current year. This database, maintained by the TOPS Lab, contains information on all police reported crashes in Wisconsin, including the crash time and location, vehicles involved, and general attributes. Highway related MV4000 crashes are manually geo-coded by WisDOT.

**WisTransportal VSPOC Archival Data Management System**

The V-SPOC system is a web-based interface for data query, data visualization, data exporting, quality reporting, and corridor analysis, built on top of a complete database archive of ITS traffic detector data (volume, speed, and occupancy) from the Wisconsin Department of Transportation (WisDOT) Advanced Traffic Management System (ATMS) for the years 1997-present. Up to this year, this archive includes more than 10 billion records from approximately 5,000 detectors statewide, with the largest concentration on interstate highways in and around Milwaukee and Madison metropolitan areas. All the detectors have been manually geocoded by the TOPS Lab, whose locations are shown in Figure 1.
Location Coding of WisLCS, VSPOC and MV4000 Data
The locations of highway crashes, detectors and work zones in the aforementioned systems are coded the Wisconsin State Trunk Network (STN) (19), the WisDOT GIS-based linear referencing system and GIS roadway network for state and federal highways in Wisconsin. Although the three datasets uses different linear referencing methods (LRMs) to align information to the STN, the locations are translated through the LRM process to a common representation based on “links” and “offsets” of the STN network. This allows for efficient matching of the work zone and crash records, deriving detector distances from work zones, and calculating the actual exposure.

DATA INTEGRATION
This procedure to integrate the three data sets includes several sub-tasks: (1) obtain the work zone length and actual duration, (2) find all crashes that occurred near or within work zones and all ITS detectors that are located upstream, within or downstream of those work zones, and (3) calculate the actual vehicle mile traveled (VMT) for work zones. The details are explained below.
Calculating Work Zone Lengths and Duration

As a linear referencing system, it is possible to convert STN location information from the underlying network representation in terms of links and offsets to one based on highway cumulative mileage. A method previously developed by the authors to calculate the highway cumulative mileage of a work zone from the begin and end locations is described in (13, 20). The length of the work zone \( i \) is calculated as:

\[
L_i = CME_{\text{End}_i} - CMB_{\text{Begin}_i}
\]  

Where \( CME_{\text{End}_i} \) and \( CMB_{\text{Begin}_i} \) are the begin and end cumulative mileage of the work zone on a highway, respectively.

It should be noted that there are cases when the work zone is on concurrent highways. If it is the case, the begin and end cumulative mileage of the work zone are different regarding to different highways. However, the length calculated would be the same. In addition, some work zones, such as bridge and ramp maintenance, are described by a single point rather than two begin and end locations. Such cases are referred to as “point closures” in this paper. In this paper, a point closure is assigned with a length of 0.25 mile, based on empirical investigation.

The WisLCS includes four Duration types to capture the different work zone schedule scenarios that may occur:

1. **Daily/Nightly**: the time of operation occurs on a daily or nightly basis as specified by the starting and ending times per each day within the start date and end date range. For example, if a daily/nightly work zone is from 10/1/2010 - 11/15/2010, 2:00 PM - 5:00 PM, the cones are dropped at 2 p.m. each day and picked up 5 p.m. each day. The work zone then has a sequence of \( N \) active periods with the total length of:

\[
\text{Duration}_i = N(EndTime_i - BeginTime_i)
\]

Where \( EndTime_i \) and \( BeginTime_i \) are the begin and end time of the day, respectively, and \( n \) is the total number of the days.

2. **Weekly**: the time of operation occurs on a weekly basis as specified by starting and ending day of week. For example, if a weekly work zone is from 10/1/2010 - 11/15/2010, MON 2:00 PM - FRI 5:00 PM, the cones are dropped at 2 p.m. every Monday and picked up 5 p.m. every Friday for each week within the start date and end date range. Similar to a Daily/Nightly work zone, a Weekly work zone has a sequence of \( N \) active periods with the total length of:

\[
\text{Duration}_i = N(EndDOWTime_i - BeginDOWTime_i)
\]

Where \( EndDOWTime_i \) and \( BeginDOWTime_i \) are the begin and end day of week with time of the day, respectively, and \( n \) is the total number of the weeks.

3. **Continuous**: the operations is continuous between the begin and end time, which is lasting less than two weeks.
Long Term: the operations is continuous between the begin and end time, lasting longer than two weeks.

It is also possible to assign Schedule Override periods for a work zone in the WisLCS. A schedule override adds an exception to the Duration element by indicating specific times in which the work zone will not be in effect. Therefore, the override periods should be deducted from the actual duration of a work zone if there is any override periods.

Spatial Correlation of Work Zones, Crashes and Traffic Detectors

As noted above, the STN linear referencing capabilities can be used to provide the cumulative mileage of the work zones, VSPOC detectors and crash locations on their associated highways as the common scale for location matching. This method also provides the necessary distance from the crash and the VSPOC detector to the work zone, respectively, for the following analysis. Figure 2 shows an example in which a crash occurred within the work zone, and there are detectors available in the upstream mainline, on and off ramps to detect traffic entering the work zone. For more details about the spatial correlation algorithm, please refer to our previous studies (13, 20).

Calculating Work Zone VMT

The VMT for work zone $i$ is calculated as:

$$VMT(i) = L_i \times Vol_i$$

Where

$L_i$ is the length of work zone $i$, and

$Vol_i$ is the total traffic volume traveled through work zone $i$ during its life cycle.
Calculating the traffic volume for a work zone is more complicated. The following steps are used:

1. Group the detectors within, immediate upstream, and immediate downstream of a work zone, into “count stations.” A count station is defined as a group of detectors providing traffic detection in a close distance for one direction of traffic. A typical count station comprises the detectors placed side by side in each lane, and the entering and exiting lanes nearby.

2. Select reliable traffic data from the count stations. Because of various causes, such as (1) detector malfunction, (2) detector removed or offline from work zone activity and (3) detection error, a comprehensive traffic data quality check is necessary to screen out reliable traffic data. Using a data quality tool developed previously for VSPOC (21), the number of good “samples” of traffic count data within in 1-minute intervals is calculated for each detector selected. If a detector has less than 80% “good” data samples over the sum of the work zone periods, it is considered unreliable to calculate the actual volume. Unreliable detectors are excluded from this study. The detectors which pass the data quality check may still have some bad or missing data, and the “bad” data is replaced by the interpolation of the immediate preceding and succeeding good data.

3. Calculate the traffic volume

The traffic volume entering the work zone can be calculated as:

\[
Vol_{i,u} = \sum_{n=1}^{N} \sum_{t \text{ period}(n)} Vol_{i,u,m}(t) + Vol_{i,u,en}(t) - Vol_{i,u,ex}(t)
\]

Where

- \(Vol_{i,u}\) is the traffic volume entering the work zone, and
- \(Vol_{i,u,m}(t)\) is the traffic count from the detectors at the mainline upstream of the work zone at time interval \(t\), and
- \(Vol_{i,u,en}(t)\) and \(Vol_{i,u,ex}(t)\) are the traffic counts from the detectors on the on and off ramps at time interval \(t\). Note that these on and off ramps are connecting the mainline after the aforementioned mainline detectors, and
- \(N\) is the number of periods for the work zone (Eq (2) and (3))

Similarly, the traffic exiting the work zone can be calculated as:

\[
Vol_{i,d} = \sum_{n=1}^{N} \sum_{t \text{ period}(n)} Vol_{i,d,m}(t) - Vol_{i,d,en}(t) + Vol_{i,d,ex}(t)
\]

Where

- \(Vol_{i,d}\) is the traffic volume exiting the work zone, and
- \(Vol_{i,d,m}(t)\) is the traffic count from the detectors at the mainline downstream of the work zone at time interval \(t\)
- \(Vol_{i,d,en}(t)\) and \(Vol_{i,d,ex}(t)\) are the traffic count from the detectors on the on and off ramps at time interval \(t\). Note that these on and off ramps are connecting the mainline upstream of the aforementioned mainline detectors, and
$N$ is the number of periods for the work zone (Eq (2) and (3)).

The key difference between equations (5) and (6) is how entering and exiting traffic is handled to approximate the actual (mainline) traffic flow within the workzone.

In many cases, the detectors within the work zone are put offline or removed during the work zone period. The total traffic volume is then calculated as the average of the upstream and downstream volume. In some cases, the detectors within the work zone are still operational during the work zone operations. The on and off ramps have two possible displacement as shown in Figure 3.

![Figure 3 Ramp Displacement](image)

Based on the two possible placements, the volumes of the upstream section and downstream section can be calculated as:

For Case (a), the upstream section volume can be calculated as:

$$Vol_{i,m,u} = \sum_{n=1}^{N} \sum_{m \in \text{period}(n)} Vol_{i,m,m}(t) - Vol_{i,m,en}(t)$$

(7)

Where

$Vol_{i,m,u}$ is the traffic volume for the upstream section, and
\( Vol_{i,m,m}(t) \) is the traffic count from the detectors at the mainline at time interval \( t \), and
\( Vol_{i,m,en}(t) \) is the traffic count from the detectors on the on ramp at time interval \( t \).

And for the downstream section:
\[
Vol_{i,m,d} = \sum_{n=1}^{N} \sum_{t \in \text{period}(n)} Vol_{i,m,m}(t) - Vol_{i,m,ex}(t)
\]
(8)

Where
\( Vol_{i,m,d} \) is the traffic volume for the downstream section, and
\( Vol_{i,m,m}(t) \) is the traffic count from the detectors at the mainline at time interval \( t \), and
\( Vol_{i,m,ex}(t) \) is the traffic count from the detectors on the off ramp at time interval \( t \).

For Case (b), the upstream section volume can be calculated as:
\[
Vol_{i,m,u} = \sum_{n=1}^{N} \sum_{t \in \text{period}(n)} Vol_{i,m,m}(t) + Vol_{i,m,ex}(t)
\]
(9)

Where
\( Vol_{i,m,u} \) is the traffic volume for the upstream section, and
\( Vol_{i,m,m}(t) \) is the traffic count from the detectors at the mainline at time interval \( t \), and
\( Vol_{i,m,ex}(t) \) is the traffic count from the detectors on the off ramp at time interval \( t \).

And for the downstream section:
\[
Vol_{i,m,d} = \sum_{n=1}^{N} \sum_{t \in \text{period}(n)} Vol_{i,m,m}(t) + Vol_{i,m,en}(t)
\]
(10)

Where
\( Vol_{i,m,d} \) is the traffic volume for the downstream section, and
\( Vol_{i,m,m}(t) \) is the traffic count from the detectors at the mainline at time interval \( t \), and
\( Vol_{i,m,en}(t) \) is the traffic count from the detectors on the off ramp at time interval \( t \).

Therefore, the upstream, within and downstream count stations provide a series of traffic volume values, and the work zone is divided into a few sub-segments by the locations of the count stations. By numbering and ordering the count stations from upstream to downstream, a general formula to calculate the work zone volume by a weighted average is:
\[
Vol_i = \sum_{s=1}^{S_i} \frac{L_s(s)(Vol_i(s) + Vol_i(s+1))}{2L_i}
\]
(11)

Where,
\( Vol_i(s) \) is the volume from count station \( s \) for work zone \( i \), and
\( L(s) \) is the length of sub-segment \( s \), which is the distance between count station \( s \) and \( s+1 \), and

\( L_i \) is the length of sub-segment \( i \).
$L_i$ is the total work zone length, and $L_i = \sum_{s=1}^{K} L_i(s)$.

In cases when there is no detection available from within the work zone, Eq. (11) is reduced to a simple average of the upstream and downstream volumes:

$$Vol_i = (Vol_{i,u} + Vol_{i,d}) / 2$$  \hspace{1cm} (12)

**RESULTS SUMMARY AND ANALYSIS**

**The Matching Results**

There are a total of 43,498 highway work zones recorded in the WisLCS from 2009 to 2012, of which 26,953 have VSPOC detector nearby or within them, and 16,545 do not.

Among the work zones with VSPOC detectors, the traffic data for 6,528 work zones is unreliable according to the aforementioned data quality screen. In summary, there are 20,425 work zones with reliable traffic data during the work zone periods, and they are used as the study set in this paper. Only 1,564 of those work zones have crash occurred. The distributions are shown in Figure 4.

![Figure 4 Work Zone Distribution](image_url)

Statewide, there are 187,731 highway crashes recorded in the MV4000 database from 2009 to 2012, of which 4273 crashes are recorded as work zone crashes. There are 2054 crashes occurred in the study set of 1564 work zones. The severity of all highway crashes, highway work zones crashes and the matched work zone crashes is shown in Table 1, using the KABCO crash injury severity scale (22).
### Table 1 Data Integration Summary

<table>
<thead>
<tr>
<th></th>
<th>All Highway Crashes</th>
<th>All Highway Work Zone Crashes</th>
<th>Study Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Count</td>
<td>Percentage</td>
<td>Count</td>
</tr>
<tr>
<td>K</td>
<td>1025</td>
<td>0.5%</td>
<td>23</td>
</tr>
<tr>
<td>A</td>
<td>5327</td>
<td>2.8%</td>
<td>116</td>
</tr>
<tr>
<td>B</td>
<td>16813</td>
<td>9.0%</td>
<td>429</td>
</tr>
<tr>
<td>C</td>
<td>26719</td>
<td>14.2%</td>
<td>776</td>
</tr>
<tr>
<td>PD</td>
<td>137847</td>
<td>73.4%</td>
<td>2929</td>
</tr>
<tr>
<td>Total</td>
<td>187731</td>
<td>100.0%</td>
<td>4273</td>
</tr>
</tbody>
</table>

Note:

K: fatal; A: incapacitating; B: non-incapacitating; C: possible; PD: property damage.

It should be noted that the study set has a lower percentage of K, A and B crashes than the total highway work zone crashes. It is because the crashes used in the study set are from work zones where there is traffic detection available (the highways with VSPOC detectors, as shown in Figure 1). The lower severity in the study set would imply a lower severity level for crashes on those highways, probably because those highways with detectors are major corridors and the work zones on them are usually well managed.

### Crash Rate and Average Crash Cost Analysis

In this section, the safety level of different types of work zones is investigated. In specific, three primary work zone attributes are covered: Duration, Closure Type and Lane Details. Duration describes the hours of operation of a work zone, and have been introduced in the previous section. Closure Type describes the type of work zone or construction project, and Lane Details provide specific work zone lane configurations.

Since different types of work zones have different average time period and lengths, a simple crash occurrence for work zones may not be sufficient. Therefore, the crash rate definition based on VMT is used. In addition, to emphasize crash severity, we also use crash cost as another index of work zone safety. The crash cost is defined as a weighted crash cost per VMT. The crash cost for a specific work zone category $N$ is calculated using Eq.(13):

$$\text{Cost} = \frac{K \cdot C_k + A \cdot C_A + B \cdot C_B + C \cdot C_C + PD \cdot C_{PD}}{\sum_{i \in N} VMT_i}$$  \hspace{1cm} (13)$$

Where,

- $K$, $A$, $B$, $C$, PD are the total number of K, A, B, C and PD crashes associated with the category of work zones,
- $C_k, C_A, C_B, C_C, C_{PD}$ are the expected cost of K, A, B, C and PD crashes, respectively,
- $VMT_i$ is the total VMT of work zone $i$, which falls in this category.
The actual values of $C_K, C_A, C_B, C_C, C_{PD}$ used in this study are based on the comprehensive costs defined by FHWA *Highway Safety Improvement Program Manual* (23), as $C_K =$ $4,008,900, C_A =$ $216,000, C_B =$ $79,000, C_C =$ $44,900$ and $C_{PD} =$ $7,400$.

**Crash Rate and Crash Cost Analysis**

Table 2 shows the total VMT (in Million), the number of crashes, the crash rates (crash per 100 million VMT) and the crash cost ($ per thousand VMT) for different work zone types. In terms of WisLCS closure types, Permit is for utility work. Maintenance is for small and short work zones lead by Counties, while Construction closures are for are WisDOT LET projects. Emergency is unplanned lane closures, such as when there is a bridge hit or pavement buckling. Special Event are temporary highway lane closures for planned community and statewide events.

<table>
<thead>
<tr>
<th>Work Zone Type</th>
<th>Total VMT (Mill.)</th>
<th>Crashes</th>
<th>Crash Rate (100 Mill. VMT)</th>
<th>Crash Cost ($ / KVMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permit</td>
<td>54.74</td>
<td>50</td>
<td>91.34</td>
<td>27.26</td>
</tr>
<tr>
<td>Maintenance</td>
<td>108.46</td>
<td>53</td>
<td>48.87</td>
<td>9.25</td>
</tr>
<tr>
<td>Construction</td>
<td>1,294.09</td>
<td>1933</td>
<td>149.37</td>
<td>47.81</td>
</tr>
<tr>
<td>Emergency</td>
<td>9.32</td>
<td>18</td>
<td>193.13</td>
<td>30.39</td>
</tr>
<tr>
<td>Special Event</td>
<td>0.08</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Overall</td>
<td>1466.70</td>
<td>2054</td>
<td>140.04</td>
<td>44.08</td>
</tr>
</tbody>
</table>

In terms of crash rates, the Emergency is the most “dangerous” type, while it is not the most dangerous from a crash cost perspective. It can be seen the general crash rates are not necessarily an indication of crash severity risk, which indicates the crashes have a very different distribution in terms of severity for the four types. Furthermore, this finding would lead to a question about choosing safety performance measures. The inconsistency would suggest that evaluation of work zone safety levels based on a single index would probably be biased.

It is worth noting that Maintenance and Emergency work zones both have a much lower crash cost compared to their overall crash rate ranking. The causes behind that could provide valuable insight about improving work zone safety.

Table 3 shows the crash rates and crash cost regarding to work zone duration types. An interesting finding is about the difference between Long Term and Continuous work zones. Continuous work zones are much shorter than Long Term; they have a median duration of about 10 hours, while Long Term work zones are all longer than two weeks. One possible reason would be the small impacts to traffic: the Continuous work zones have much smaller amount of work, and have the flexibility to avoid busy hours of the day because of the short duration. In addition, the Weekly have a very high Crash Cost. A close look at the crashes associated with Weekly work zones indicates that it is likely to
be a random outlier event because of the low VMT. There is one fatal crash occurred
within the Weekly work zones, which significantly increases the crash cost. If that

Table 3 Crash Rate by Work Zone Duration Type

<table>
<thead>
<tr>
<th>Work Zone Duration Type</th>
<th>Total VMT (Mill.)</th>
<th>Crashes</th>
<th>Crash Rate (100 Mill. VMT)</th>
<th>Crash Cost ($ / KVMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily/Nightly</td>
<td>433.50</td>
<td>510</td>
<td>117.65</td>
<td>40.51</td>
</tr>
<tr>
<td>Weekly</td>
<td>9.49</td>
<td>17</td>
<td>179.22</td>
<td>351.09</td>
</tr>
<tr>
<td>Long Term</td>
<td>529.22</td>
<td>1041</td>
<td>196.70</td>
<td>62.15</td>
</tr>
<tr>
<td>Continuous</td>
<td>494.50</td>
<td>486</td>
<td>98.28</td>
<td>21.98</td>
</tr>
<tr>
<td>Overall</td>
<td>1466.70</td>
<td>2054</td>
<td>140.04</td>
<td>44.08</td>
</tr>
</tbody>
</table>

Table 4 shows the crash rates and crash costs based on different lane configurations.
Comparing from the Full Closure to the Shoulder, Median and Off Roadway, it
demonstrates a consistent trend of decreasing of crash rate and crash cost, which implies
that less impacts to the traffic (less portion of roadway closed) might lead to less crash
risk to the traffic. Such finding is consistent with comparison between the Continuous
and Long Term work zones conducted previously. It is surprising to see that Various
Lanes Closed work zones, which have different lane closed during their operations
periods, become the safest. Investigating the causes would be part of the future work of
the authors.

Table 4 Crash Rate by Lane Configuration Type

<table>
<thead>
<tr>
<th>Work Zone Type</th>
<th>Total VMT (Mill.)</th>
<th>Crashes</th>
<th>Crash Rate (100 Mill. VMT)</th>
<th>Crash Cost ($ / KVMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Closure</td>
<td>86.47</td>
<td>467</td>
<td>540.07</td>
<td>136.82</td>
</tr>
<tr>
<td>2 or more Lanes Closed</td>
<td>29.41</td>
<td>79</td>
<td>268.63</td>
<td>76.17</td>
</tr>
<tr>
<td>One Lane Closed</td>
<td>498.14</td>
<td>696</td>
<td>139.72</td>
<td>53.27</td>
</tr>
<tr>
<td>Shoulder, Median and off Roadway</td>
<td>470.81</td>
<td>568</td>
<td>120.64</td>
<td>33.89</td>
</tr>
<tr>
<td>Flagging Operation</td>
<td>1.19</td>
<td>2</td>
<td>168.24</td>
<td>45.30</td>
</tr>
<tr>
<td>Lane Restriction</td>
<td>216.18</td>
<td>177</td>
<td>81.88</td>
<td>30.48</td>
</tr>
<tr>
<td>Various Lanes Closed</td>
<td>164.50</td>
<td>65</td>
<td>39.51</td>
<td>8.81</td>
</tr>
<tr>
<td>Overall</td>
<td>1466.70</td>
<td>2054</td>
<td>140.04</td>
<td>44.08</td>
</tr>
</tbody>
</table>
Table 5 shows the crash rates and crash costs based on different work zone highway function classes, for both the study set and the 2009-2012 state overall. The state statistics were calculated using the Wisconsin DOT VMT statistics (24), and the crash records from the MV4000, excluding deer crashes and parking lot crashes.

Because the coverage of VSPOC detectors are mostly on the interstate highways as shown in Figure 1, the results on the two categories of Urban Interstate and Rural Interstate are believed to be representative. Comparing the work zone rates and the state overall rates, the significant increase (about 3 times) of crash rates is observed. In addition, although Rural Interstate has a much lower work zone crash rate than the Urban Interstate, the crash costs are about 10% apart. The work zone crashes on Rural Interstate tend to be more severe, for which one possible reason would be related to higher traveling speeds.

Table 5 Crash Rate by Work Zone Highway Function Class

<table>
<thead>
<tr>
<th>Work Zone Type</th>
<th>Study Set</th>
<th></th>
<th></th>
<th>State Overall</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total VMT</td>
<td>Crash</td>
<td>Crash Rate</td>
<td>Crash Cost</td>
<td>Crash Rate</td>
</tr>
<tr>
<td>Urban Interstate</td>
<td>521.83</td>
<td>1130</td>
<td>216.55</td>
<td>74.56</td>
<td>76.80</td>
</tr>
<tr>
<td>Rural Interstate</td>
<td>185.36</td>
<td>309</td>
<td>166.70</td>
<td>61.36</td>
<td>55.01</td>
</tr>
<tr>
<td>Urban Other</td>
<td>652.17</td>
<td>582</td>
<td>89.24</td>
<td>21.11</td>
<td>179.97</td>
</tr>
<tr>
<td>Rural Other</td>
<td>107.34</td>
<td>33</td>
<td>30.74</td>
<td>5.67</td>
<td>89.22</td>
</tr>
<tr>
<td>Overall</td>
<td>1466.70</td>
<td>2054</td>
<td>140.04</td>
<td>44.08</td>
<td>102.72</td>
</tr>
</tbody>
</table>

Discussion

A number of findings from this study are worthy of mentioning:

1. Work zone safety performance measures

In this study two types of measures are used: (1) crash rate, the number of crashes every 100 million VMT, and (2) the crash cost, the average crash cost every 1000 VMT. The results show that general crash rates do not necessarily imply overall risk in terms of crash severity, and the two measures cannot be used interchangeably. That is, there are situations in which crashes would be more likely to occur, but crashes tend to be minor. On the other hand, when the sample size becomes smaller (only a few dozens of crashes), the crash cost would be less stable. An example presented in the previous section is that the Weekly work zones have a very high crash cost because there is a single fatal crash. These findings would suggest that selecting a good safety performance measure is not always straightforward, and to be more objective and unbiased, multiple performance measures would be more preferable instead of one.

2. Work zone setting and optimization for safety

The results of comparing different work zone type, duration and lane configuration suggests that some types of work zone setting have low crash rates and crash costs than
other: planned work zones with shorter duration, and fewer lanes closed are general safer than unplanned, longer and more lanes closed ones. This finding suggests that splitting large and long work zones into smaller ones could lower crash risks, which would be worth integrating into the equation for work zone scheduling and improve the overall work zone safety and efficiency.

CONCLUSIONS AND FUTURE WORK
Developing a better understanding of work zone crash and the nature of high risk work zones are essential to incorporate meaningful and effective safety considerations into work zone planning and operations. Ideally, a variety of data sources including crash reports, work zone attributes, and traffic detection are needed to support work zone safety analysis. However, the data is usually very limited in terms of quantity, quality and completeness, especially for traffic data. Most existing studies have to rely on estimated average daily traffic (ADT) because actual traffic data is unavailable, which introduces biases and errors.

In this paper, a systematic work zone safety analysis was provided for work zones in Wisconsin based on integration of lane closure records, operations traffic data and crash reports. A method is developed to obtain the actual vehicle miles traveled (VMT) for each work zone. The VMT based crash rates and crash cost for each category of work zone are calculated. Based on the comprehensive and systematic review of statewide work zone safety, it indicates that: (1) different work zone settings have different impacts on the crash rate and crash severity, and (2) planned work zones with shorter duration, and fewer lanes closed are general safer than unplanned, longer and more lanes closed ones. These findings can help develop safety countermeasures for better work zone management.

The key of this study is the successful alignment of previously disparate data sources to a common linear referencing system. Future work would include as follows: (1) integrating weather and road surface condition data as additional inputs into the analysis, and (2) including crashes rate and cost into the work zone scheduling equation to improve work zone safety and efficiency.

ACKNOWLEDGEMENT
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Reference


