**Abstract**

Work zone safety studies have traditionally relied on historical crash records—an approach which is reactive in nature as it requires crashes to accumulate first before taking any preventive actions. However, detailed and accurate data on work zone crashes are often not available, as is the case for Australian road work zones. The lack of reliable safety records and the reactive nature of the crash-based safety analysis approach motivated this research to seek alternative and proactive measures of safety. Various surrogate measures of safety have been developed in the traffic safety literature including time to collision, time to accident, gap time, post encroachment time, required deceleration rate, proportion of stopping distances, lateral distance to departure, and time to departure. These measures express how close road-user(s) are from a potential crash by analysing their movement trajectories. A review of this fast-growing literature is presented in this paper from the viewpoint of applying the measures to untangle work zone safety issues. The review revealed that the use of the surrogate measures is very limited for analysing work zone safety, although numerous studies have used these measures for analysing safety in other parts of the road network, such as intersections and motorway ramps. There exist great opportunities for adopting this proactive safety assessment approach to transform work zone safety for both roadworkers and motorists.

**Introduction**

While road construction and repair is essential for maintaining and improving the mobility and safety of all road users, the process of building safer roads and roadsides needs to be managed to minimize risks to both motorists and roadworkers. Reports from highly motorized countries including the Netherlands, United States and Great Britain show that around 1-2% of road fatalities occur in work zones (NWZSIC, 2012a, b; SWOV, 2010). Numerous studies have found that crash rates increase significantly during roadworks compared with pre-work periods (Khattak et al., 2002; SWOV, 2010). Work zone crashes are also reported to be more severe than other crashes (Pigman and Agent, 1990).

Compared to some other countries, relatively little is known about roadwork crashes across Australia, primarily because it is difficult to identify roadwork crashes in official records (Debnath et al., 2013; Haworth et al., 2002). Thus, it is difficult to obtain accurate
comparative information on crash rates, crash severity and other variables of interest. Based on New South Wales (NSW) data, it is estimated that nationally each year at least 50 deaths and 750 injuries occur in crashes at roadworks with a cost of more than $400 million (Debnath et al., 2012). Approximately 1% of traffic crashes reported in NSW in 2007 (n=45,395) occurred at a ‘roadworks/detour/diversion’ location (RTA, 2008). Of these crashes (n=467), about 3% were fatal and 43% involved injury, while the remaining 54% of crashes resulted in property damage only.

Under-reporting of work zone crashes has been identified as a substantial issue (see Debnath et al., 2013 for a detailed discussion). In Queensland, work zone crashes are identifiable in police-reported crash records only if ‘roadworks’ is reported as a circumstance contributing to the crash and a public vehicle is involved. A similar situation exists in Victoria, where work zone crashes only need to be reported as such if the work zone is determined by police to have contributed to the crash. For example, a crash may not be recorded as a work zone crash where a driver crashed due to speeding or dangerous driving in work zone. These deficiencies in crash data limit the scope for untangling the common hazards in Australian work zones and therefore little is known about their relative contributions to crash causation. In addition to these issues which impede identification of crashes at roadworks, there could also be significant underreporting of incidents where a public vehicle is not involved (whether inside or outside a work zone) or the severity level is low. Workplace Health and Safety (WHS) datasets provide an alternative source of information about roadworks incidents but these datasets are managed separately by respective organisations and include data from their worksites only and there is little consistency among the datasets. There is likely to be significant under-reporting in WHS datasets as well, in that they may not include details or consequences of incidents occurring outside of the roadworks site or when the workers were not there (despite the presence of roadworks contributing to the incident).

In addition to the problems related to the unavailability of work zone crash data unavailability and under-reporting, there are some other significant challenges and limitations in using the crash data. Firstly, it is necessary to have sufficiently large number of crashes accumulated to obtain statistically sound inferences from analysis of crash records. Crashes are rare, random and sporadic events, and therefore a long time period (e.g., 3-5 years or more) is required to obtain a statistically sufficient sample size. The problem of low sample size is even worse when crash counts are segregated by locations, types and time periods in order to derive in-depth understanding of crash causation processes. In the case of work zone crashes, the problem of low sample size is more significant than normal road sections, particularly because work zones exist for short durations (ranging from several hours to a few months) and the likelihood of obtaining a large sample size is smaller in work zones than in normal road sections. Secondly, a lack of detailed information in the crash records often restricts safety analysts’ ability to understand the crash causation process. Thirdly, under-reporting of crashes—particularly uneven distribution of under-reported extents in regard to types of road users, locations, severity levels of crashes etc.—is a common problem in many jurisdictions. Finally, this reactive approach of safety analysis using historical crash records might be unethical in nature (Chin and Quek, 1997; Chin and Debnath, 2008; Debnath and Chin, 2006) as it requires sufficiently large number of crashes to take place first, before any preventive or corrective measures are taken.

The abovementioned challenges and limitations in using crash records for analysis of safety encouraged researchers to use various surrogate measures of safety, such as travel speeds, speed variances, erratic manoeuvres, and traffic conflicts. Among these measures, traffic
conflicts are the most popular and have been the subject of a significant amount of research. Numerous studies have been conducted to develop and apply traffic conflicts as an alternative to the historical crash records in safety analyses of traffic systems in various parts of transport networks (e.g., Chin and Quek, 1997; Chin and Debnath, 2009; Davis et al., 2011; Debnath and Chin, 2007, 2010; Debnath et al., 2011; Minderhoud and Bovy, 2001; Sayed et al., 2013; Songchitruxa and Tarko, 2006; Svensson and Hydén, 2006; Tarko, 2012; Vogel, 2003). Traffic conflicts utilise critical traffic interactions to analyse safety deficiencies proactively and eliminate the need for the significant waiting time involved in the crash-based approach. Various measures of traffic conflicts have been developed in the traffic safety literature including time to collision, time to accident, gap time, post encroachment time, required deceleration rate, proportion of stopping distances, lateral lane deviation, and time to edge crossing. These measures express how close road-users are from a potential crash by analysing their movement trajectories.

Despite numerous studies successfully using traffic conflicts as surrogates of crashes, little research effort has been devoted to using traffic conflicts for understanding the safety issues in work zones. Most of the work zone studies in the literature used surrogate indicators related to travel speeds and speed variances, but the use of traffic conflicts as surrogates of crashes has yet to be comprehensively explored. Therefore, great opportunities exist for adopting this proactive safety assessment approach to transform work zone safety for both roadworkers and motorists. This paper presents a synthesis of the fast-growing literature on measures of traffic conflicts from the viewpoint of applying the measures to untangle the safety issues in work zones. By critically reviewing the definitions and assumptions of the various safety measures, their suitability to the work zone context is evaluated.

Method

In order to understand the suitability of surrogate safety measures in the work zone safety context, first it is necessary to have a thorough understanding of the prevalent safety issues in work zones. For this purpose, relevant articles were identified in various online databases including the Engineering Village, Science Direct, Google Scholar, and Transport Research International Documentation. This was followed by another search of the same databases to identify relevant articles related to surrogate safety measures and their application in work zone safety assessment. The scope for both review exercises was confined to articles which were published in the English since 1990.

Safety issues in work zones

Safety hazards in work zones are typically identified through analyses of historical crash data. Many studies have used crash records to examine the factors contributing to frequency of work zone crashes (e.g., Chen and Tarko, 2012; Khattak et al., 2002). Others have analysed factors affecting injury severity of work zone crashes (e.g., Khattak et al., 2002; Qi et al., 2013). However, the approach of using crash data is often hampered by the lack of detail in official datasets (Yang et al., 2013) and the likelihood of under-reporting in work zone crashes (Debnath et al., 2013).

Despite the challenges, these studies derived useful inferences regarding work zone safety issues. Generally, the literature suggests that the likelihood of crash occurrence increases during construction activities and most crashes occur in the activity area. Multivehicle and heavy vehicle crashes are generally overrepresented in work zone crashes, while rear-end and sideswipe crashes are the predominant work zone crash types. Factors potentially...
contributing to work zone crashes include speeding, driver inattention, distraction and confusion, lack of (worker) conspicuity, ineffective signage and lack of information, among others. The prevalence of each of these factors evidently varies according to the operational and environmental characteristics of a work zone, but non-compliance with reduced speed limits is a major concern for most work zones.

Findings from several Queensland studies (Debnath et al., 2014a; Debnath et al., 2012, 2013, 2014b) show that driver actions are responsible for creating most of the hazards in work zones. Speeding, noncompliance with traffic signage and traffic controller instructions, and distracted driving were the common hazardous behaviours in work zones. Other sources of hazards include improper working environment (e.g., working in wet weather, inadequate escape path) and not maintaining safety practices (e.g., tampering with reversing beepers).

Synthesising these findings, along with those from analysis of common incidents in work zones (Debnath et al., 2013) reveals that the approach area of a work zone (i.e., upstream of work area) is the most safety critical area identified both from the perceptions of roadworkers and drivers’ speed profiles. Common types of incidents, such as work area intrusion, rear end crashes, and traffic controller hit by vehicle generally occur in this area. Moreover, motorists are guided to stop, change lanes and/or reduce speed to minimum levels while travelling through this area. These actions create more conflicts among vehicles and increase the variability of speeds in a traffic stream, thus increasing the likelihood of crashes.

Surrogate safety measures in the context of work zone safety

Typically work zone safety studies have used travel speeds, changes in speeds, and speed variances as surrogate measures of safety. Many studies (see Debnath et al., 2012 for a review) have measured mean speeds and degree of speeding (at different levels of speeds over posted limits) to evaluate different interventions to improve work zone safety. Changes in the mean speeds and degrees of speeding between the conditions—without interventions and with interventions—were used as the indicators of the effectiveness of the interventions. Speed variances were also used as indicators of safety levels by some researchers (e.g., Ishak et al., 2011; Miller et al., 2009). Use of traffic conflicts for safety evaluation in work zones is not very widespread among work zone researchers yet, arguably because the measures of conflicts require significant processing and analysis of traffic movement data (Ullman et al., 2013). However, traffic conflicts have been the subject of considerable research in the context of other road sections and have gained a good level of acceptance among road safety researchers as crash surrogates.

Uses of traffic conflicts as crash surrogates are known in literature as Traffic Conflict Techniques (TCTs). The essential principle of the TCTs is based on the idea that interactions between road users can be described as a continuum of safety related events with crashes at the tip of a pyramid of traffic events (Svensson and Hydén, 2006). The key hypothesis is that all traffic interactions—situations in which two or more road users are close enough in space and time and the distances between them is decreasing over time—can be ranked in a safety hierarchy with crashes at the top. The interactions located just below the crashes in which road users managed to avoid a collision are called quasi-crashes (commonly known as traffic conflicts). Following the ranking principle (i.e., decreasing severity of interactions), the interactions at the bottom of the hierarchy are the safe passages for which the probability of crash is zero. The key advantage of the TCTs over the crash-data-based approach is that larger numbers of conflicts can be observed within a shorter time period compared to crash data, as conflicts occur considerably more frequently than crashes. Therefore, it is possible to
obtain statistically sound inferences by analysing conflicts over a significantly shorter time period. In addition, the TCTs solve the ethical problem (i.e., reactive approach) by investigating safety deficiencies proactively.

Traffic conflicts are defined based on observable evasive actions taken by drivers to avoid crashes and ‘nearness to crashes’ is defined in terms of either space or time proximity between interacting vehicles. The former method of defining conflicts leads to ‘field-observer’ based measurement of conflicts which is subjective in nature and often questioned for reliability and inter/intra-coder biases (Chin and Quek, 1997), whereas the later method is more objective and leads to quantitative measurement of conflicts. The quantitative measurement method is usually preferred as it is objective and provides a quantitative measure of conflicts which is interpretable in terms of closeness to crashes (Chin and Quek, 1997).

Table 1 Summary of traffic conflict measures

<table>
<thead>
<tr>
<th>Measures</th>
<th>Definition</th>
<th>Assumptions/Conditions</th>
<th>Suitable for measuring work zone crash risk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temporal Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to collision (TTC)</td>
<td>Expected time for two vehicle to collide, if course and speed remain unchanged</td>
<td>Collision course must exists</td>
<td>Rear-end, head-on, hit fixed objects, hit traffic controllers, work zone intrusion crashes</td>
</tr>
<tr>
<td>Time to accident (TA)</td>
<td>TTC at the time driver takes evasive actions</td>
<td>Same as TTC</td>
<td>Same as TTC</td>
</tr>
<tr>
<td>Post Encroachment Time (PET)</td>
<td>Time difference between two vehicles sharing a common space</td>
<td>Vehicles to have transversal trajectories. A fixed projected point of collision is required</td>
<td>Angle crashes</td>
</tr>
<tr>
<td>Encroachment time, Initially attempted PET</td>
<td>Derivatives of PET</td>
<td>Same as PET</td>
<td>Same as PET</td>
</tr>
<tr>
<td>Time headway, Gap time</td>
<td>Time difference between two consecutive vehicles</td>
<td>Identical trajectories of vehicles</td>
<td>Rear-end (TTC is preferred over these measures)</td>
</tr>
<tr>
<td><strong>Non-temporal measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion of stopping distances</td>
<td>Ratio of distance available for manoeuvring to that of the necessary stopping distance</td>
<td>Single vehicle to stop by taking evasive actions</td>
<td>Hit fixed objects, hit traffic controllers, work zone intrusion crashes</td>
</tr>
<tr>
<td>Required deceleration rate (RDR)*</td>
<td>Maximum uniform rate at which vehicle must decelerate to avoid a crash</td>
<td>Collision course must exist</td>
<td>Rear-end, hit fixed objects, hit traffic controllers, work zone intrusion crashes</td>
</tr>
<tr>
<td>Uncomfortable declaration</td>
<td>Rate of deceleration above a threshold</td>
<td>Same as RDR</td>
<td>Same as RDR</td>
</tr>
<tr>
<td>Lateral distance to departure (LD)</td>
<td>Lateral distance of the front right tyre (for departure to the right) to the right edge of paved area</td>
<td>Single vehicle event</td>
<td>Work zone intrusion crashes</td>
</tr>
<tr>
<td>Time to departure (TD)</td>
<td>Time remaining to depart from paved road area</td>
<td>Single vehicle event</td>
<td>Work zone intrusion crashes</td>
</tr>
</tbody>
</table>

* also known as Deceleration rate to avoid a crash

Various measures of traffic conflicts have been developed for quantitative measurement of the conflict severities which can be broadly grouped into two categories: temporal and non-temporal measures. The temporal measures express nearness to crash in terms of time...
remaining to a crash or the time difference between two vehicles passing through a common point. On the other hand, the non-temporal measures express the risk of crash in terms of the closest distances between two vehicles or the rate of change in positions of the vehicles by driver actions. Suitability of the traffic conflicts measures for analysing work zone safety issues are discussed in the succeeding sections. A summary of the measures is presented in Table 1.

**Temporal measures**

Time to collision (TTC) is the most commonly used temporal measure of conflict severity. TTC is defined as the expected time for two vehicles to collide if course and speeds of both vehicles remain unchanged (Sayed et al., 2013). A prerequisite to measure TTC is that a collision course must exist between the vehicles involved. Therefore, it is not capable of measuring conflicts where a collision course does not exist. However, a traffic interaction where vehicles pass each other with a narrow space/time margin (i.e., no collision course exists) could pose significant risk of crash if any of the vehicle’s course/speed changes at the moment just before the crossing happens. Since TTC can vary throughout the interaction process, researchers considered different points at which TTC should be measured. The most commonly used measure is the minimum registered value of TTC in an interaction process and the TTC at the onset of taking evasive actions (Chin and Quek, 1997). The TTC at the time of taking evasive actions is termed as Time to accident (TA) and is used widely in the Swedish Traffic Conflict Techniques (Svensson and Hydén, 2006). To measure TA, the evasive actions must be observable. However, researchers (e.g., Chin and Quek, 1997) have argued that measuring conflicts depending on observable evasive actions could be misleading.

TTC has an advantage over the other conflict measures in that the critical TTC value of an interaction (e.g., the minimum value) can be compared with time measures related to driver’s driving ability. For example, a common method of identifying the ‘serious conflicts’ (i.e., those conflicts which are close to crashes in the safety hierarchy) is to compare the critical TTC values with driver’s perception reaction time (Chin and Quek, 1997). Conflicts with critical TTC values lower than the perception reaction time indicate that there might not be enough time for drivers to react and take evasive actions to avoid a crash.

A review of literature showed one study in the work zone safety area (Gao et al., 2013) used TTC to identify rear-end conflicts in two Chinese freeway work zones. Severity of conflicts was rated into three categories using rather arbitrary threshold values: serious conflicts (TTC between 0s and 2s), light conflicts (TTC between 2s and 6s), and potential conflicts (TTC more than 6s). Based on their analysis of number of conflicts, they argued that the TTC can effectively be used for work zone safety evaluation. The need for future research on establishing appropriate links between TTC and probability of rear-end crashes was highlighted.

The prerequisite existence of a collision course makes the TTC and TA measures more suitable to measure traffic conflicts where two vehicles have identical or almost identical trajectories (i.e., travelling in a same lane) than to measure conflicts where vehicles have crossing trajectories (i.e., vehicles travelling from two adjacent approaches in an intersection). In the work zone context, crossing conflicts scenarios are not very common (except for roadworks in urban areas), but identical trajectory conflicts are very common (e.g., vehicles stopped or slowed down due to closure or merging of lanes at road sections under maintenance). The TTC and TA measures are therefore highly suitable for measuring
conflicts related to rear-end, head-on, and hitting a fixed-object/traffic-controller type crashes. Conflicts relating to sideswipe crashes might be possible to measure using the measures as well, but the calculations of the measures would be more complicated than those of the other crash types (see Laureshyn et al., 2010).

Based on the TTC concept, Minderhoud and Bovy (2001) proposed two more explorative measures – Time exposed TTC (TET) and Time integrated TTC (TIT). From a TTC profile of a driver, TET is computed as the sum of time periods when the instantaneous TTC values fall below a specified threshold value of TTC, which theoretically is the boundary between safe and safety-critical traffic interactions. TIT uses the integral of the TTC profile which falls below the TTC threshold and express conflict severity in units of square of seconds. These two measures do not rely on observable evasive actions, but suffer from the limitation of the existence of a collision course. Moreover, they are highly data-intensive and attainable only in a simulation environment (Songchitruksa and Tarko, 2006).

Post encroachment time (PET) is another temporal measure that overcomes the major limitations of the TTC family. PET is the time lapse between end of encroachment of a vehicle on a potential collision point and the time that the other vehicle actually arrives at that point (Songchitruksa and Tarko, 2006). It is especially suitable for measuring conflicts in which two vehicles pass over a common spatial point or area with a temporal difference, regardless of the collision course existence criterion. For example, the PET measure is suitable for measuring crossing conflicts where two vehicles approach each other in an intersection from right angle approaches. Although PET overcomes this limitation of TTC, it suffers from a couple of major drawbacks. Firstly, only those conflicts involving vehicles with transversal trajectories can be measured by PET. Conflicts involving vehicles with similar or nearly opposite trajectories cannot be measured because of the absence of any point of collision. Secondly, to measure PET a fixed projected point of collision is required, rather than one that changes with the dynamics of vehicle interactions.

Several derivatives of the PET measure have also been proposed in the literature (FHWA, 2003), such as Time headway, Gap time, Encroachment time (ET), and Initially attempted PET (IPET). Time headway and Gap time express the time difference between two consecutive vehicles in the same lane. The former relates to the time difference measured between the front bumpers of the vehicles and the later relates to the time difference measured for the clear gap between the vehicles. As their definitions suggest, these measures would be suitable for measuring conflicts involving vehicles with identical trajectories (rear-end crashes for example). However, comparing the critical values of the measures with relevant thresholds of serious conflicts could be a significant concern in safety analysis. From a comparative study using headway and TTC as conflict measures, Vogel (2003) recommended that TTC should be used for safety evaluations instead of headway. The ET and IPET measures express conflict severity by using similar principles of the PET measure, so are constrained by one/both of the limitations of PET.

Non-temporal measures

In addition to time-based measures, some other measures that explain spatial or kinematic characteristics of vehicle interactions have been proposed for measuring traffic conflicts. A spatial measure—the Proportion of stopping distance (PSD)—represents the ratio of the distance available for manoeuvring to that of the necessary stopping distance to a projected point of collision (FHWA, 2003). PSD would be suitable for measuring the crash risk at
approaches of work zones, where vehicles are often required to slow down or stop according to the instructions of stop/slow traffic control operation or traffic lights.

A kinematic measure—the Required Deceleration Rate (RDR)—is the maximum uniform rate at which a vehicle must decelerate to avoid a collision. Similar to the TTC measure, the RDR measure assumes that two vehicles or a vehicle and an object are on a collision course. Therefore, the RDR measure might be suitable for measuring the crash risk at road work zone approaches as well. The review of literature identified three work zone safety studies using conflict measures related to deceleration rate. Gao et al. (2013) used ‘Deceleration rate to avoid crash (DRAC)—the rate at which a follower vehicle is required to decelerate in order to avoid a crash with a leader vehicle—for estimating rear-end crash probability in freeway work zones. They found the results obtained using the measure were more convincing than those obtained through a TTC measure, however the TTC measure was preferred as it can classify conflicts by severity levels and is easier to implement than the other measure. Meng and Weng (2011) also used a similar approach for estimating rear-end crash risk in work zone activity area using the DRAC measure. The crash risk was computed as the probability that a given DRAC exceeds it maximum available deceleration rate, which was assumed to follow a truncated normal distribution. It should be noted that the RDR and the DRAC measures are conceptually the same. In another study, Ishak et al. (2011) used ‘uncomfortable deceleration (UD)—deceleration rate above 10 ft/sec^2—as measure of safety in an evaluation of joint and conventional lane merge configurations in freeway work zones using simulated data. The UD measure differs from the RDR and DRAC measures in terms of the threshold values used to define a conflict.

For measuring single vehicle conflicts related to departure from the road, Tarko (2012) developed three departure proximity measures: lateral distance to departure (LD) and two forms of time to departure. In the case of road departure to the right, the LD is measured as lateral distance of the front right tyre to the right edge of the paved road area. The two time-to-departure measures were calculated by assuming constant speed along straight path (TD1) and constant lateral speed (TD2). Findings from driver simulator experiments showed encouraging results that actual numbers of road departures were within the confidence intervals of the LD and TD1 estimates, but were outside for the TD2 measure. Given the potential of these measures for measuring road-departure type events, these measures might be useful for examining safety issues related to departure from work zone lanes. It is noteworthy to mention that often work zones have a complicated lane structure (curved and narrow lanes with provision of closed lanes) and therefore intrusion into the work zone is a common type of work zone incident.

Conclusions

This paper has examined the suitability of surrogate measures of safety into understanding the safety issues in work zones. By critically reviewing the fast-growing literature on surrogate measures of safety from the viewpoint of applying these measures to untangle the safety issues in work zones, it revealed that the use of the surrogate measures is very limited for analysing work zone safety. However, the few studies that have used surrogate measures in the work zone safety context produced meaningful results. The review also revealed that work zone safety issues in the approach areas, such as rear end crashes, public vehicle intrusion into work areas, fixed-object/traffic-controller hit type crashes, could effectively be diagnosed using the surrogate measures developed in the literature. Given the successful and wide use of surrogate measures in other parts of the road network, such as intersections and
motorway ramps, there exist great opportunities for adopting this proactive safety assessment approach to transform work zone safety for both roadworkers and motorists.

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