THE UTILIZATION OF KINETIC ENERGY FOR THE SAFETY ASSESSMENT OF INTERSECTIONS

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ABSTRACT

The use of crash data based methodologies for safety evaluation has been usually problematic due to the many shortcomings such as, unavailability and low quality of historical crash data. Other than crash data based analysis, development of micro-simulation models in conjunction with surrogate safety measures is shown to have potential to complement traditional safety analysis. However existing measures for the assessment of intersection safety such as post-encroachment time (PET) and time to collision (TTC) are related to the probability of a collision to occur, but it cannot be directly linked to severity. Thus, this study aims to develop a safety index that considers crash probability as well as severity. By utilizing the change in the total kinetic energy before and after the collision, angle of collision and PET, the proposed safety index is derived and its implications are discussed. Several previously videotaped signalized intersections in Nagoya City, Japan are utilized to extract vehicle trajectories. The relationship between the estimated distribution of the proposed index and crash records of the same sites is presented. It is concluded that the proposed safety index is successful in providing a similar ranking of different signalized intersection to the ranking which is based on the number of crashes occurred at each site. The proposed index presents a rational blend between the probability and the severity of conflicts which can be used in comparison analysis. It can assess policy makers in prioritizing different sites for safety improvements projects.

Keywords: traffic conflict, safety index, intersections, kinetic energy, post-encroachment time

INTRODUCTION

Despite the large amount of safety modelling research, absolute numbers of crashes and crash rates are still difficult to predict accurately. This has led to increase interest in traffic conflict technique and related surrogate measures as an approach to assess the safety of traffic facilities. Traffic conflict technique is a procedure which was defined the first time by Perkins et al. (1969) through identifying traffic conflict patterns for over 20 corresponding crash patterns at intersections. Although several studies (Migletz et al., 1985 and Lu et al., 2011) have found that traffic conflicts are good surrogates to crashes, direct correlation between the characteristics of traffic conflicts and accident frequency or severity is still not proven.

Several indices are proposed to measure traffic conflicts such as the post-encroachment time (PET) and the time to collision (TTC). These indices certainly indicate the probability of a collision to occur, but it cannot be directly linked to its severity. Thus, other indices are utilized to investigate the conflicts' severity such as speed. In general, a single reliable index that can present the overall safety performance including crash frequency and severity is still missing. Therefore, this study aims to propose a new index which can present the probability of a collision to occur and its expected severity as well without the need to observe actual crashes. Furthermore, this study provides a comprehensive comparison with some relevant existing measures.

After introduction and literature review, the assumption behind the development of the proposed safety index and its derivation are discussed. The rationality of the proposed index in presenting various conflict conditions such as different conflict angles, speeds and timings is demonstrated. A comparison between crash records at several signalized intersection in Nagoya City and empirically estimated crash indices at each site is presented to investigate the reliability of the proposed index. Finally, the paper ends up with summary of the results, conclusion and future works.

LITERATURE REVIEW

The frequency or rate of reported crashes is commonly used for the evaluation of safety at intersections. When following such approach, comprehensive historical crash data is necessary comprising at least several years. Highway Safety Manual (2010) summarizes decades of traffic crash studies and proposes crash frequency/rate predictive methods considering geometric characteristics of traffic facilities and traffic conditions. These methods are subjected to many limitations in applicability and considered influencing factors. Thus, this approach is suitable for long term a posterior assessments. Here comes traffic conflict technique (TCT), in which surrogate indices are usually the measures for safety or risk, as an applicable alternative method that does not need long term measurements as compared to the crash data analysis.

Various conflict indicators have been suggested for the safety evaluation of traffic facilities. Some of these indices are defined in Table 1. In general, Gettman and Head (2003), Allen *et al.* (1978), Tang and Nakamura (2009) found that time to collision TTC and post-encroachment time PET are ranked as the best measures for the analysis of safety at intersections in the consideration of ease of measurement, and application to conflict types.

Table 1 - Summary of existing traffic conflict safety measures

No.	Safety indicators	Definition and description
1	**Gap Time (GT)** Gettman and Head (2003)	Time lapse between completion of encroachment by turning vehicle and the arrival time of crossing vehicle if they continue with same speed and path.
2	**Time to Collision (TTC)** Gettman and Head (2003)	Expected time for two vehicles to collide if they remain at their present speed and on the same path.
3	**Post-Encroachment Time (PET)** Gettman and Head (2003)	Time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of crash.
4	**Deceleration Rate (DR)** Gettman and Head (2003)	Rate at which through vehicle needs to decelerate to avoid crash
5	**Proportion of Stopping Distance (PSD)** Gettman and Head (2003)	Ratio of distance available to maneuver to the distance remaining to the projected location of crash.
6	**Initially Attempted Post-Encroachment Time (IAPET)** Gettman and Head (2003)	Time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of crash and the completion time of encroachment by turning vehicle.
7	**Time to Zebra (TTZ)** Andras (1998)	The distance to zebra crossing divided by the speed at any given moment in time.
8	**Possibility Index for Collision with Urgent Deceleration (PICUD)** Uno et al. (2002)	Possibility that two consecutive vehicles might collide assuming that leading vehicle applies its emergency. PICUD is the distance between two vehicles considered when they completely stop.
9	**Time to Accident (TA)** Archer (2005)	The time that goes from somebody starts an evasive maneuver, until a collision would have occurred if the two involved road users had continued with unchanged speed and direction
10	**Deceleration to Safety (DST)** Pirdavani et al. (2010)	The necessary deceleration to reach a last calculable PET

TTC is the best measure applying to rear-end conflicting events, while PET is the best measure applying to the angle conflicting events. Moreover, Tang and Nakamura (2009) proposed the PET as a measure for safety performance during intergreen intervals. A PET during a change of phases is defined as the elapsed time from when the last clearing vehicle in the previous phase passes the conflict point till when the first entering vehicle of the subsequent phase arrives there. In their study, PET is used to estimate the number of conflicts. Conflicts are defined as encroachments between two vehicles with a PET of less than t sec. However, the PET alone cannot assess the safety of angle collisions, for example the impulse of the vehicles involved in the conflict is not considered, although it is a very

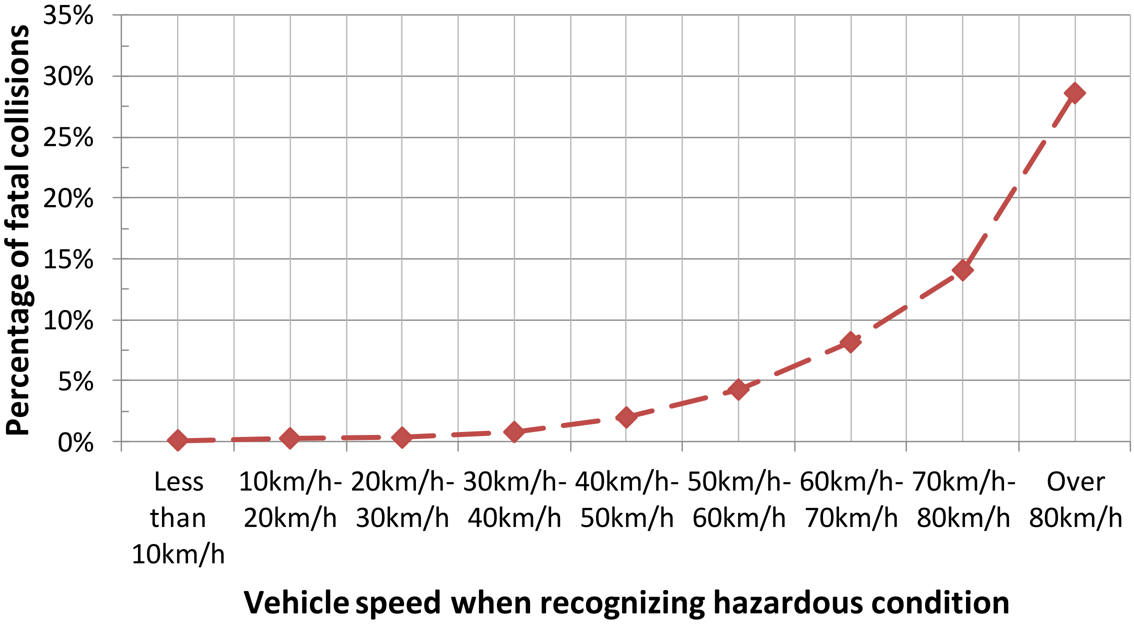


Figure 1 Relationship between vehicle speeds when facing hazardous conditions and percentage of fatal collisions from total number of collisions in ordinary roads in Japan in 2011

important factor in determining the probability of a collision to occur. Therefore other indices have been used to evaluate the severity of a potential conflict such as the speed distribution of conflicting vehicles, conflict angle and acceleration distribution as summarized by Gettman,and Head (2003).

Several previous studies found that vehicle speed when a crash occurs (crash speed) significantly contributes to the severity of that crash (Kloeden et al., 2001, Wang and Abdel-Aty, 2008, Pesanen, 1992 and Kruysse, 1991). Kloeden et al. (2001) concluded that the risk of involvement in a casualty crash increases more than exponentially with increasing free travelling speed above the mean traffic speed in rural roads. Moreover, Pesanen (1992) found that a collision speed of 50 km per hour of a vehicle to pedestrians will lead to the risk of pedestrian fatal injury almost eight times higher as compared to a speed of 30 km per hour. According to the Accident statistics in 2011 of Japan National Police Agency, a significant (95% confidence level) exponential relationship was found between vehicle speeds when facing hazardous conditions and percentage of fatal collisions from total number of collisions in ordinary roads as shown in Figure 1. This clearly shows that higher speeds at conflict points may contribute to higher conflict severities. Therefore it is reasonable to use the speeds of conflicting vehicles at the conflict point as an indicator for the severity of the conflict, assuming that these speeds would be very close to the crash speed if the conflict becomes a real crash. Sobhani et al (2011) developed a comprehensive simulation based approach for the safety assessment of road locations. The proposed methodology contains two main parts. Firstly, the estimation of number and severity level of conflicts using an existing micro-simulation model. The severity of simulated conflicts is studied based on the required braking rates (RBR). The second part is the measurement of potential injury severity of each simulated conflict by modelling the relationship between driver behaviour and vehicle speed at the time of the rash and crash injury level using the Australian Crash In depth Study

(ANCIS) database (Logan et al., 2006). However, The amount and characteristics of crash data used in model development is not presented. Furthermore, the proposed methodology evaluates crash probability and potential severity separately.

METHODOLOGY

This paper proposes a methodology to assess the safety performance without the need to have crash data and their detailed characteristics. It only needs empirical or simulated conflict data. In this study, the term conflict is defined as the condition where two consecutive vehicles pass a common point along their paths with a time difference of less than 5 seconds. Assuming vehicles' approaching speed as 50 km/hr, which is the most common speed limit in urban streets in Nagoya City, the distance that the vehicles can cruise in 5 seconds is approximately 70m which indicates that any two consecutive vehicles with a time difference of more than 5 seconds are not likely to exist simultaneously inside the intersection. Thus, in this study a conflict is only observed if the time difference between the arrivals of the two consecutive vehicles is equal or less than 5 second.

To propose an index capable of rationally representing the safety level of various conflict types, the main characteristics of any conflict; probability and severity should be considered in a reasonable way. The proposed index in this study is mainly based on the released kinetic energy after a collision. The released energy, which supposes to affect on the persons inside the vehicles, is a rational and reasonable indication of the expected severity level. Simultaneously, the released energy is weighted by the probability of the conflict to occur which is based on the Post Encroachment Time (PET). The mathematical formation of the proposed conflict index (CI) is shown in Equation (1).

$$CI = \frac{\alpha \Delta K_e}{e^{\beta PET}} \quad (1)$$

Where α is a parameter to represent the percentage of the released energy that will affect the persons inside the vehicles, ΔK_e is the change in total kinetic energy before and after collision, the term $\mathbf{e^{\beta PET}}$ is used to weight conflicts depending on the probability of a crash to occur which is represented by PET. PET is defined as the time difference between two successive vehicles where the first vehicle clears the conflict area and the second arrives at the conflict area. As the PET becomes shorter, the likeliness of the crash becomes higher.

However since different conflict types with similar PET values might have different crash probability due to the location and size of the conflict area. Therefore an adjustment parameter β (sec^{-1}) is proposed to reflect the effect of conflict type on crash probability.

Since the denominator is unit-less, the CI has the unit of energy. Thus it represents the potential kinetic energy to be released if the conflict turned into a collision, calibrated to the probability of collision occurrence. In reality, the released kinetic energy due to a collision depends on many factors such as vehicle speed, type and shape.

The advantage of this crash severity estimation mechanism using momentum conservation is to evaluate the condition after crashes by simple assumptions from these limited data. Because of the above reason, the methodology is worthwhile although the actual crash mechanism is rather complicated

Assumptions and Development

To estimate the change in kinetic energy ΔK_e before and after the collision, the following assumptions are made:

- The vehicles undergo a perfectly inelastic collision.
- The two vehicles move with the same speed together after the collision.
- The friction between the vehicles and the road can be neglected.
- The loss in energy reflects how much energy is released if the collision occurs.
- The system is isolated, where the momentum will be conserved.

To demonstrate how the proposed index is estimated, the conflict between clearing right turning vehicles (in left-hand traffic as operated in Japan) and entering though vehicles during the intergreen time is chosen as the basic conflict scenario for analysis and comparison.
Figure 2 illustrates the assumed kinetic energy concept after a collision. Since the collision environment is assumed as being isolated, the momentum is conserved along both reference axes as shown in Figure 2c. Thus Equations (2) and (3) can be derived. By solving these equations, the change in kinetic energy ΔK_e can be estimated as shown in Equation (4).

$$m_1 u_1 \sin\theta_1 + m_2 u_2 \sin\theta_2 = (m_1 + m_2) v \sin\theta_3 \tag{2}$$

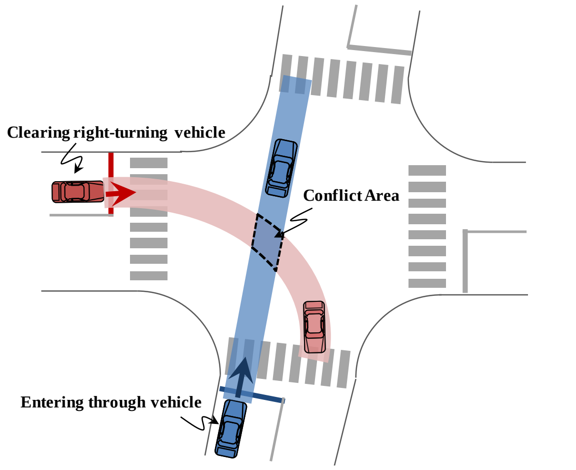
$$m_1 u_1 \cos\theta_1 + m_2 u_2 \cos\theta_2 = (m_1 + m_2) v \cos\theta_3 \tag{3}$$

$$\Delta k_e = \left(\frac{1}{2} m_1 u_1^2 + \frac{1}{2} m_2 u_2^2\right) - \frac{1}{2}(m_1 + m_2) v^2 \tag{4}$$

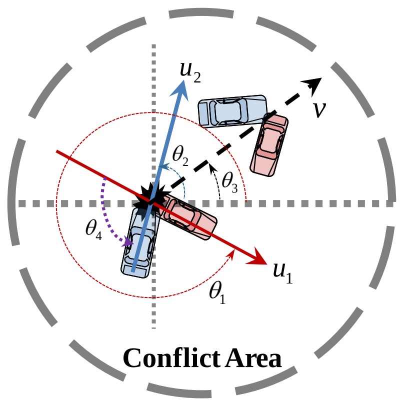
The physical characteristics of vehicles such as weight, shape and cross-section affect the amount of released energy due to a collision. However in this study, vehicle weight is the only considered factor.

Setting of Parameters α and β

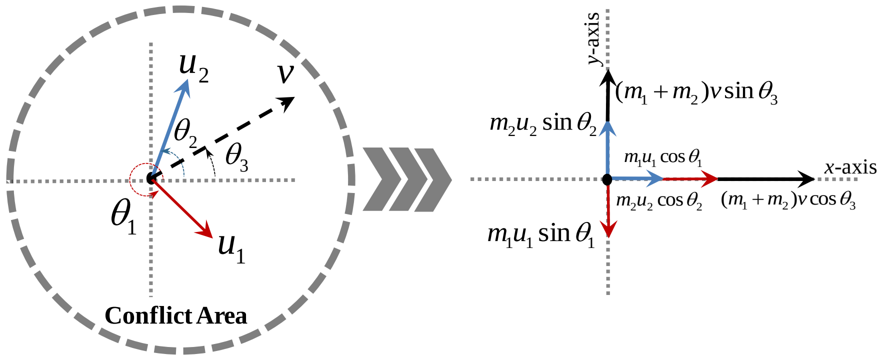
As defined in the methodology, α represents the percentage of the released energy that will affect the people inside the vehicles. It ranges between 0 and 1. This proportion depends on the speed of the conflicting vehicles, vehicle size and weight, vehicle body design and the presence of vehicle safety features such as airbags. For simplification, in this study it is assumed that all the released energy after a collision will directly affect the people inside the vehicles and thus α is assumed as 1.
Since crash probability is presented using PET, parameter β is an adjustment parameter for the crash probability considering conflict type. At a specific predicted PET between two consecutive vehicles, the probability of this conflict to become a crash might not be the same for various types of conflicts that have different movements, right-turning and left-turning, and different surrounding conditions such as lightening. Since in this study the safety index is estimated for one type of conflict, thus β is assumed as 1.



a) Angle collisions between right-turning and cross traffic



b) Assumed collision mechanism



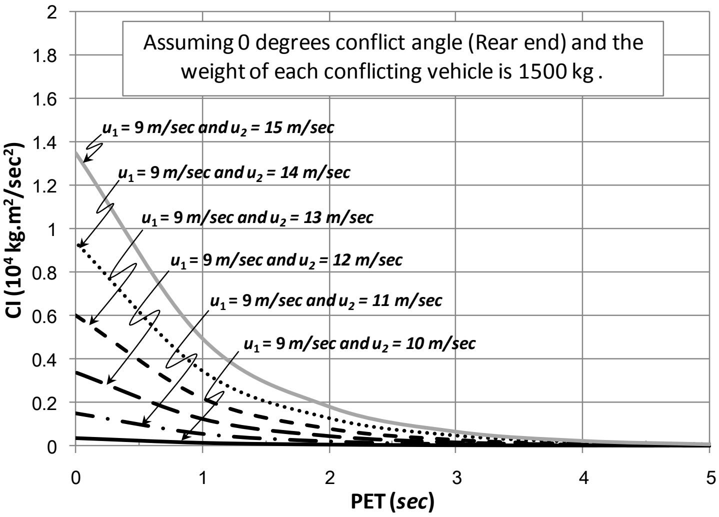
c) Momentum analysis along reference axis

Where u_1 is speed of the clearing right-turning vehicle (*m/sec*), u_2 is the speed of the entering through vehicle (*m/sec*), v is speed of clearing right-turning vehicle and entering though vehicle after collision (*m/sec*), θ_4 is the conflict angle, θ_1 is the angle between clearing right-turning vehicle and the positive x-axis at the conflict point (*degrees*), θ_2 is the angle between entering through vehicle and the positive x-axis at the conflict point (*degrees*), θ_3 is the angle between the collided vehicles and the positive x-axis after collision (*degrees*), m_1 is the mass of the clearing right-turning vehicle (*kg*) and m_2 is the mass of the entering through vehicle (*kg*).

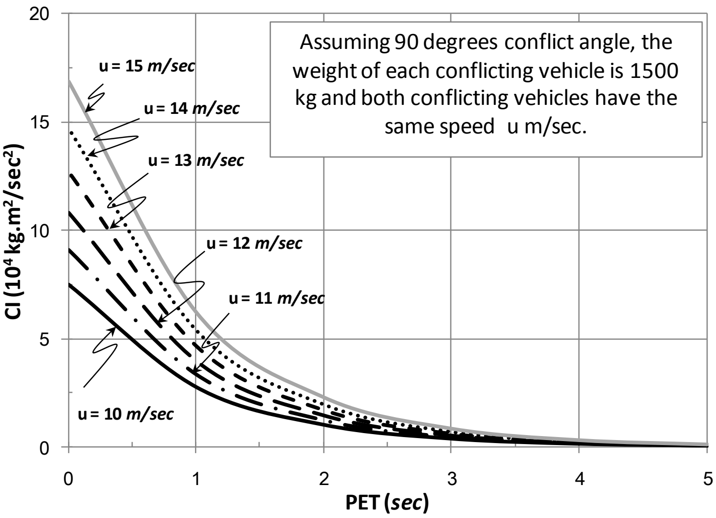
Figure 2 The estimation energy loss ΔK_e due to angle collisions

SENSITIVITY ANALYSIS

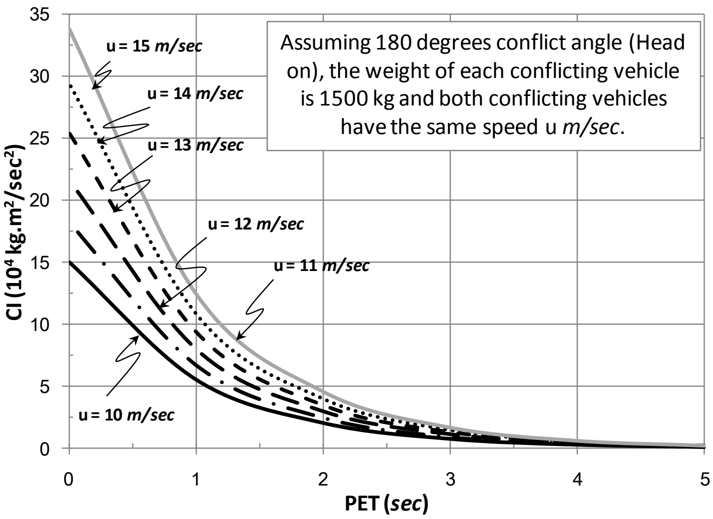
To demonstrate the sensitivity of CI to PET, conflict angle and conflicting vehicles speed, Figure 3 is presented. It assumes that the conflicting vehicles have equal weights of 1500kg. Figure 3a) assumes that the conflicting vehicles have the same direction of movement (0 degree conflict angle). As expected the value of CI decreases as PET increases which is rational. If PET becomes higher than 5 seconds or vehicle speed is less than 9 *m/sec*, the value of CI becomes negligible. It is important to remember that the proposed index blends the probability and the severity of a potential conflict in a single value. Thus if PET is very high, the probability that the collision will occur is low which leads to low CI. Simultaneously, if the speed of the conflicting vehicles is low, the estimated CI will be low as well.



a) 0 degree conflicts (Rear end)



b) 90 degree conflicts (angle conflicts)



c) 180 degree conflicts (Head on)

Figure 3 The sensitivity of CI to PET and the speed of conflicting vehicles

Table 2 - Surveyed sites for the comparison analysis and related crash data

Intersection name	Analyzed conflicting streams a)		Video Survey date	Intersection size	Turning angle (deg.)	Right turning vehicle demand veh/hr
	Right Turning	Through		W-E×N-S a)		
Hiroji-dori 1	W	S	24/2/2010 7:00-10:00	39×50	88	-
	S	E			95	-
	N	W			95	-
Sunadabashi	W	S	6/27/2008 7:30-11:00	53×30	90	140
	N	W			91	400
Taiko-dori_3	E	N	10/13/2009 7:30-10:30	76×57	85	-
	W	S			84	76
	N	W			95	76
Atsutajingu-minami	E	N	21/07/2009 7:00-12:00	50×50	119	-
	W	S			119	-
	S	E			61	-
	N	W			61	84
Suemori-dori 2	E	N	11/18/2008 9:00-12:00	58×60	112	-
	W	S			88	112
	S	E			93	240
	N	W			67	136

a) Where N is north, S is south, W is west and E is east.

Furthermore at a specific PET, when the speeds of the conflicting vehicles increase, CI increases as well. This is quite rational since it reflects that the conflict becomes more severe as the speed of any of the conflicting vehicles increases.

Figure 3b) assumes 90 degrees conflict angle while Figure 3c) assumes 180 degrees conflict angle. CI increases as the conflict angle increase indicating more severe conditions which is reasonable since the released energy at the moment of collision would be greater as the angle between the colliding vehicles increases.

COMPARISION ANALYSIS

In order to investigate the reliability of the proposed index, previously collected video data at five signalized intersection in Nagoya City, Japan were utilized (Table 2). Note that the left-hand traffic is applied in Japan. The analyzed conflict is the one between the last clearing right-turning vehicle and the first entering through vehicle of the following signal phase (during the intergreen time). The analyzed sites are characterized with high through traffic demand. Thus, the occurrence of this type of conflict mainly depends on the presence of turning vehicle at the end of the exclusive right turning phase which is functions of the demand and arrival pattern of right-turners.

Table 2 presents the characteristics of the surveyed sites including geometry, traffic and survey date. All sites are signalized intersections with exclusive right-turn phases. Crash records for each intersection are obtained from Aichi Police Department for 6 years from January 2004 to December 2009. Table 3 presents the total number of recorded crashes that involve right-turning vehicles. It is important to mention that in this study, it is assumed that

Table 3 - Surveyed sites for the comparison analysis and related crash data

Intersection name	Number of crashes[a)] in 2004~2010
Hiroji-dori 1	2
Sunadabashi	9
Taiko-dori_3	10
Atsutajingu-minami	13
Suemori-dori 2	9

a) Crashes between clearing right turning vehicles and entering through traffic only.

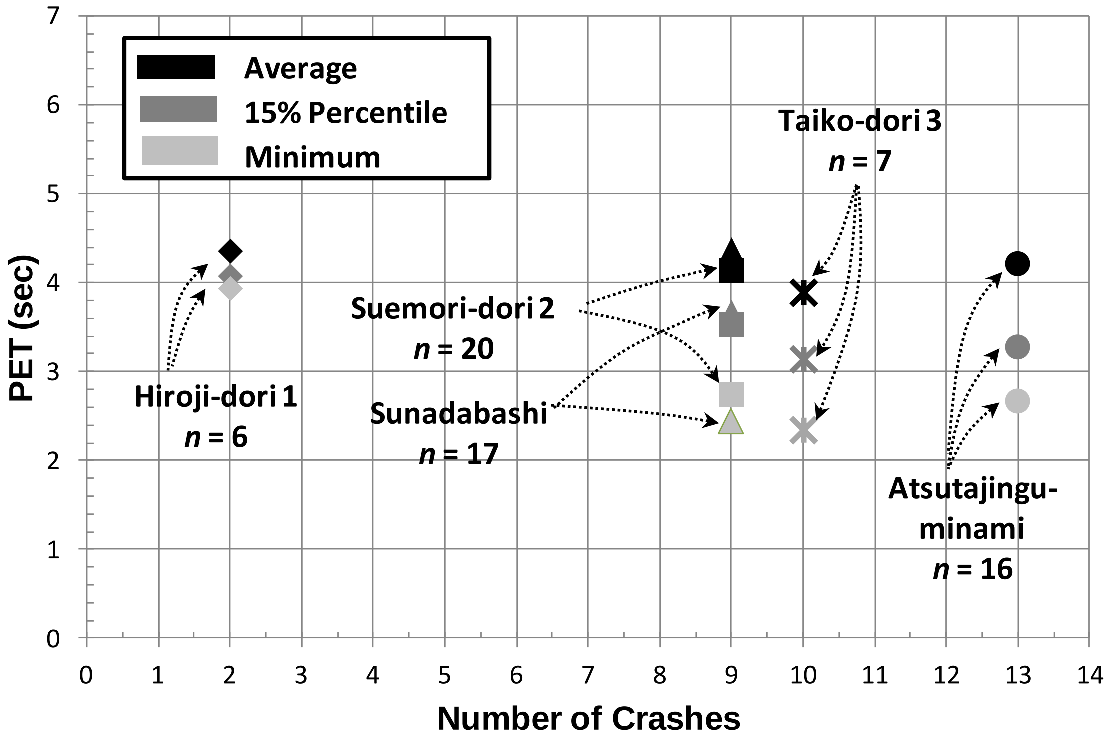


Figure 4 The relationship between PET to number of angle crashes at different signalized intersections

existing geometric and operational characteristics of the sites did not change from 2004 to 2009.

After extracting the trajectories of last clearing right-turning vehicles and first entering through vehicles in each cycle using image processing program “TrafficAnalyzer” (Suzuki and Nakamura, 2006), the position of conflict points, vehicle arrival time and vector speeds at these points are estimated. In this program, manually-tracked vehicle positions in the image data are transferred to world coordinates by projective transformation. Then, Kalman smoothing method is applied to estimate the vehicle speed. Only conflicts with PETs equal or less than 5 sec are considered and accordingly CI is estimated.

Figure 4 illustrates the relationship between observed PETs (<5 sec) and number of crashes between right-turning vehicles and through traffic. There is no clear relationship between both parameters which clearly questions the ability of PET alone to represent the safety level of signalized intersections.

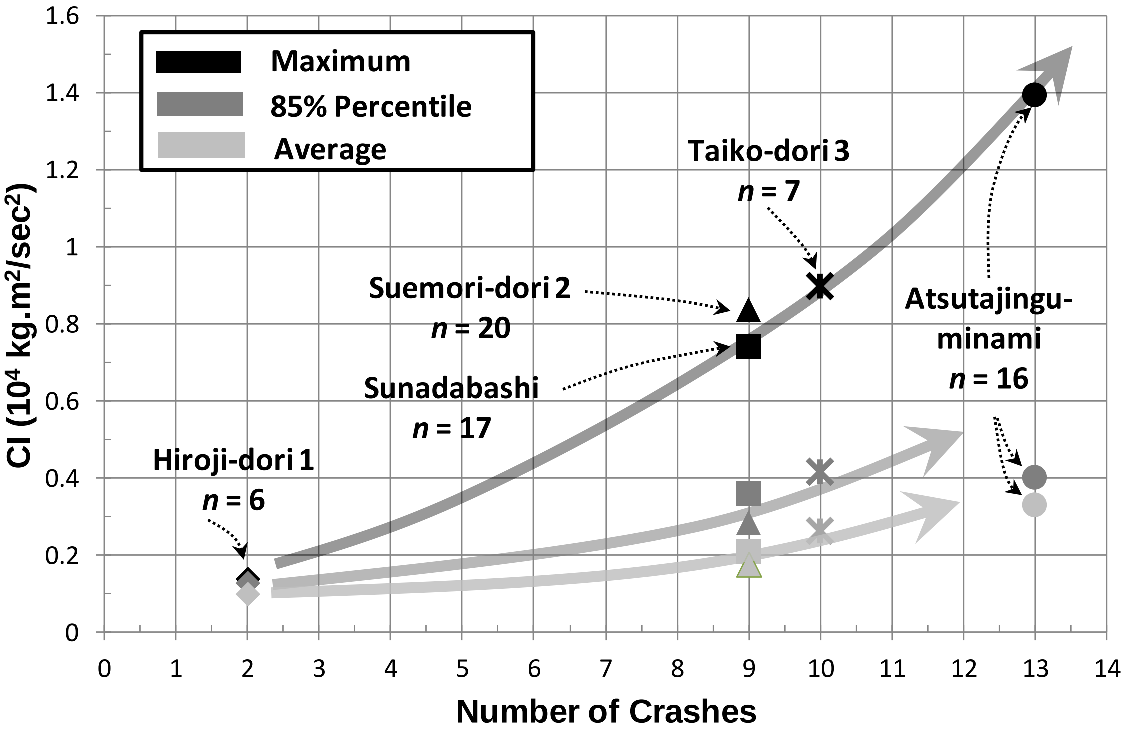


Figure 5 The relationship between CI to number of angle crashes at different signalized intersections

Figure 5 shows the relationship between estimated CI and number of crashes at the analysis sites. It clearly shows significant positive exponential relationships where the estimated CI increase as the number of crashes increases. The positive exponential relationship applies to the estimated maximum (R^2 = 0.994), 85th percentile (R^2 = 0.886) and average (R^2 = 0.951) CI values. This supports the rationality and reliability of the proposed index as a tool for conducting comparative safety analysis. However it is important to mention that the proposed index in its current form cannot be used to represent absolute crash frequencies at different sites.

CONCLUSION AND FUTURE WORKS

A new conflict index CI that considers crash probability as well as severity is proposed. It mainly consists of the change in the total kinetic energy before and after the collision, and PET. The change in the kinetic energy depends on vehicle speeds, weight, and conflict angle. Several previously videotaped signalized intersections in Nagoya City are utilized to investigate the rationality and reliability of the proposed index in representing the relative safety levels of different intersections by comparing the estimated CI distributions with crash numbers for 6 years from January 2004 to December 2009.

It is concluded that the proposed safety index is successful in providing a similar ranking of different signalized intersection to that which is based on the number of crashes occurred at each site. Furthermore, it is found that estimated maximum, average and 85th percentile conflict indices have significant exponential relationships with crash numbers. Information on the severity of recorded crashes are not available. Because of that it was not possible to investigate the relationship between CI and conflict severity, which is a future task. Comparison between estimated CI and crash numbers/severities for different types of conflicts is necessary to provide concrete validation of the proposed index.

In general, the proposed index presents a rational blend between the probability and the severity of conflicts which can be used in comparison analysis. It can assess policy makers in prioritizing different sites for safety improvements projects.

Providing concrete validation and calibration is necessary before using the developed index in conflict analysis. Furthermore, finding appropriate settings of parameters α and β is an important and challenging issue.

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