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COMPARATIVE ANALYSIS OF SAFETY PERFORMANCE INDICATORS BASED ON INDUCTIVE LOOP DETECTOR DATA

ABSTRACT

Conflicts in traffic stream have been detected by different safety performance indicators. This study aims to empirically investigate the differences between different indicators in detecting rear-end conflicts and assessing the risk in an uninterrupted flow. Micro-level data of a 24-hr traffic stream (including 6,657 vehicles) were captured using inductive loop detectors installed on a rural freeway section. Different indicators (Time Headway (H), Time to Collision (TTC), Proportion of Stopping Distance (PSD), Deceleration Rate to Avoid Collision (DRAC) and Stopping Distance Index (SDI)) were used to measure each car following event in a bivalent state (safe/unsafe). Unsafe events associated with each indicator were detected and common unsafe events characterized by different indicators were identified. Temporal distributions of rear-end collision risks associated with each indicator at 15-min intervals were also compared. Finally, the 15-min risk values based on different indicators were categorized and compared across three levels (Low, Medium and High). Data mining and statistical techniques showed that while SDI is the single most conservative indicator, DRAC and TTC detect a few risky events but very equal ones. In almost all conflicts associated with TTC, headway is still lower than the critical threshold. However, there exist considerable risky events based on headway which are still safe according to TTC. Comparison of PSD and TTC also declares that almost all conflicts associated with TTC are also risky according to PSD.

1. INTRODUCTION

Road Safety has been conventionally defined as "*the number of accidents (crashes), or accident consequences, by kind and severity, expected to occur on the entity during a specified period*" [1]. However, researchers have noted the deficient aspects of studies focusing on crash counts as the only data source. For example, Lord and Mannering reviewed data and methodological issues in research based on crash data [2]. Studies of crash counts are based on a reactive approach that is inherently limited by the available data and includes no information about pre-crash events. Such an approach can hardly be advocated from an ethical point of view, because it requires crashes to happen in a relatively long time before choosing the effective remedial countermeasures. While road crashes are recognized to be consequences of traffic conflicts, count-based studies only rely on reported crashes and do not include all likely interactions between the road users [3].

Focus on all possible interactions between road users (from undisturbed interactions to risky conflicts) provides a proactive approach in traffic safety investigation. Conflict in this approach was first introduced by Perkins and Harris [4]; however, Amundsen and Hydén provided a practically applicable and universally accepted definition as *"an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged"* [5]. Performance studies of individual road users based on this approach give an insight into potential crash situations and actions for prevention [6].

The proactive approach has offered a wide range of methodologies to capture the conflicts in a traffic stream. Primitive methods relied on simple judgments by trained human observers on the road. However, recent innovations (such as high quality detectors and automated analysis techniques) help researchers readily measure the safety of interactions between the road users in terms of more objective safety performance indicators (also called "proximal safety indicators" or "surrogate safety measures").

The degree to which the surrogates are correlated with real crashes is questionable (e.g. see [7,8]). To date very few indicators have been thoroughly validated (e.g. [9]). However, different safety performance indicators have already been applied in previous studies using real world data (e.g. [3,10,11]) or data generated by well-calibrated micro-simulation models (e.g. [12]).

To detect conflicts in a traffic stream, different indicators use different aspects of interactions. For example, Laureshyn et al. categorized indicators to those describing proximity in space, proximity in time and the intensity of necessary evasive action [13]. Some indicators are suitable to capture conflicts from the data obtained on a road length, whereas a few of indicators are applicable if the data are gathered in a cross section [14]. Some indicators are also exclusively applicable on special features (intersections).

Almost all safety indicators are adopted based on the primitive principles of Newtonian mechanics of movement; however, the classic principles of kinematics are not always applicable to examine the differences between safety performance indicators. Moreover, it may be hypothesized that while a given interaction between two road users is assessed to be safe in terms of a variety of performance indicators, it may be recognized as risky by others.

Reviews of literature indicate that few previous studies examined the differences between performance indicators in capturing the conflicts. For example, comparing headway and time to collision, Vogel concluded that these indicators are independent of each other [15]. Oh et al. implemented a prototypical project to measure the real-time risk of car-following events, based on the analysis of image processing of video captured data [16]. They compared safety evaluation methods in terms of the time each tracked vehicle was driving in an unsafe manner, based on time to collision (TTC) and stopping distance index (SDI) criteria. Guido et al. used videotaping instruments to extract trajectories of vehicles moving alongside the ring and entering/exiting points of a roundabout in Italy [3]. Tracking individual vehicles in a limited time period, they used different performance indicators to evaluate safety. Analysis of risky car-following events showed that different indicators cause different locations around the roundabout to be recognized as having high safety problems.

A holistic focus on comparative analysis of safety performance indicators has been the subject of very few studies to date (e.g. see [3] and [15]). The present study aims to empirically investigate the differences between a number of indicators in terms of equally identification of conflicts and risks thereof in car-following events captured in a cross section in an uninterrupted traffic flow.

2. SAFETY PERFORMANCE INDICATORS

If data in use are gathered in a cross section, a range of safety performance indicators (and associated thresholds) may be applicable in detecting vehicular risky following events (conflicts). In this research focus was placed on performance indicators addressed more in previous studies as well as being capable to be measured based on micro-level data obtained by inductive loop detectors at cross sections. Assuming that vehicle speed does not change considerably in the short period before and after the measurement section station at the cross section (isoveloxic assumption [17]), the cross-sectional attributes obtained can be assigned to a short distance from the section.

2.1 Time Headway

Highway Capacity Manual (HCM) defines the Time Headway (H) as *"the time in seconds, between two successive vehicles passing a point, measured from the same common feature of both vehicles"* [18]. (Equation 1)

$$H = t_i - t_{i-1} \tag{1}$$

where t_i and t_{i-1} denote time of passage (s) for the following and leading vehicles, respectively.

Vogel presents different headway thresholds recommended or enforced in different countries (from 0.9 s in Germany to 3.0 s in rural areas of Sweden) [15]. Moreover, a limit of more than 2 s is usually advised for time headway by the European Governments [19].

2.2 Time to Collision

Time to Collision (TTC) was first defined by Hayward in 1972 as *"the time required for two vehicles to collide if they continue at their present speeds and on the same path"* [20]. TTC is measured using Equation 2.

$$TTC_i = \frac{X_{i-1}(t) - X_i(t) - l_i}{\dot{X}_i(t) - \dot{X}_{i-1}(t)} \quad \forall \dot{X}_i(t) > \dot{X}_{i-1}(t) \tag{2}$$

where $X(t)$ and $\dot{X}(t)$ denote the position and speed of vehicle at time t, respectively (i and i-1 subscripts are used to address the following and leading vehicles, respectively) and l represents the length of vehicle.

Svensson regarded the time to collision as a conflict indicator [21]. Different thresholds for TTC have been introduced as criteria to distinguish rear-end conflicts (e.g. see [22]). However, Van der Horst argued that 1.5 s (corresponding to the minimum perception and reaction time) is TTC critical value; below this value the following vehicle is assumed to be in conflict or on an unavoidable collision path [23].

2.3 Proportion of Stopping Distance

Allen et al. defined the Proportion of Stopping Distance (PSD) as the ratio of the distance to the potential collision point to the acceptable minimum stopping distance [24] (Equation 3).

$$PSD = \frac{RD}{MSD} \tag{3}$$

In this equation, RD represents the remaining distance to the potential point of collision and MSD shows the acceptable minimum stopping distance, which can be measured according to Equation 4.

$$MSD = \frac{V^2}{2d} \tag{4}$$

where V is the approaching velocity and d is the acceptable maximum deceleration rate. PSD should be always more than 1.0 to assure the safety of the following event.

2.4 Deceleration Rate to Avoid Collision

Cooper and Ferguson were one of the first to define Deceleration Rate to Avoid Collision (DRAC) as a measure of conflict [25]. For vehicles driving in the same direction, DRAC (m/s²) is calculated using Equation 5. In this equation, V and X show the velocity (m/s) and location (m) of vehicles (i and i-1 subscripts represent the following and the leading vehicles, respectively) and L_{i-1} denotes the length of the leading vehicle.

$$DRAC_i = \frac{(V_i - V_{i-1})^2}{2 \times [(X_{i-1} - X_i) - L_{i-1}]} \tag{5}$$

Archer suggests that if DRAC for the following vehicle exceeds a threshold of 3.35 m/s², its following situation can be regarded as a conflict [26]. This threshold is a bit lower than what is recommended by AASHTO

Green Book as the deceleration rate available in most vehicles (i.e. 3.4 m/s²) [27]. Moreover, Cunto and Saccomanno assumed that two times of Maximum Available Deceleration Rate (2*MADR) follows a truncated normal distribution with an average of 7.42 m/s² and standard deviation of 0.24 m/s² [28]. In another study the same authors assumed a normal truncated distribution with an average of 8.45 m/s², standard deviation of 1.40 m/s² and the upper and lower limits of 12.68 m/s² and 4.23 m/s², respectively for 2*MADR for small vehicles on dry pavements [29].

2.5 Rear-End Collision Risk Index

To calculate the risk of rear-end collision on freeway cross sections, Oh et al. developed a collision risk index based on the concept of Safe Stopping Distance [30]. According to this concept, to avoid rear-end collision in a car following event, the stopping distance of leading vehicle should be larger than that of the following vehicle (Equation 6).

$$V_L h + \frac{V_L^2}{2a_L^{dec}} - l_L > V_F t_R + \frac{V_F^2}{2a_F^{dec}} \tag{6}$$

where V, a^{dec} and l represent velocity (m/s), deceleration rate (m/s²) and length of vehicle (m), respectively (subscripts L and F represent the leading and following vehicles, respectively). t_R is the brake reaction time (s) and h denotes the time headway between the two vehicles.

Oh et al. propose Stopping Distance Index based on the comparison of Stopping Distances of leading and following vehicles, as in Equation 7. SDI in this equation represents the Stopping Distance Index.

$$SDI = \begin{cases} 0 & (safe) & if \ V_L h - V_F t_R - l_L + \left(\frac{V_L^2}{2a_L^{dec}} + \frac{V_F^2}{2a_F^{dec}}\right) > 0 \\ 1 & (unsafe) & otherwise \end{cases} \tag{7}$$

The rear-end collision risk index (RCRI) is then proposed as the ratio between the total number of unsafe events and the maximum possible number of car following situations over a certain time interval (Equation 8).

$$RCRI = \frac{\sum_i SDI_i}{N_{car}^{Max}(T/3600)N_l} \tag{8}$$

where N_{car}^{Max} is the maximum number of car following events per hour (derived from freeway capacity), T is the analysis duration (s) and N_l is the number of freeway lanes in the analysis direction.

3. DATA

If properly installed, inductive loop detectors (ILDs) have been shown to be useful in measuring disaggregate attributes (namely: speed, length and time of passage) of individual vehicles passing over the sensors

[30]. Automated ILDs have been used for gathering traffic data in Iran for about a decade. By the end of 2011, rural highways of the country (with total length of more than 12,600 km) will have been equipped with 531 pairs of ILDs [31].

In this study inductive loop sensors connected to a personal computer (PC) as a programmable electronic data logger enable registration of the passage time for each vehicle. The shape of received vehicle signature is related with the length (and type) of the passing vehicle. Installing two successive sensors also allows for vehicular speed measurement.

Empirical data used in this study were captured by ILDs installed on a four-lane divided rural freeway, connecting Arak to Salafchegan in Markazi province in central Iran. For each lane, a pair of sensors embedded in the pavement, were connected to a data logger to gather traffic data. Using a GPRS (General Packet Radio Service) modem, data packets (including speed, length and time of passage of individual vehicles passing over the sensor) were transmitted every 5 minutes to the main server in the central office in Tehran. Micro-level traffic data obtained in a 24-hour duration on a working day of January 2012 on the slow moving lane (including 6,657 vehicles) were included in the analysis. Limiting the data to the slow-moving lane tends to cover more vehicles, of different types and of a wider range of speeds.

4. METHODS

A "car-following event" (called "event" hereinafter) is conventionally defined in this study as *an action in which a vehicle runs behind a leading vehicle on the same lane and direction, regardless of its speed and time gap*. Using the different safety performance indicators reviewed in the next section and summarized in *Table 1*, bivalent safety state of each event *i* based on each performance indicator *j* can be determined by Safety Index SI_{ij} as Equation 9. As shown in this table, depending on maximum deceleration rate available for the following vehicle (fixed or variable), safety analysis based on two kinds of DRAC and SDI have been conducted in this study.

$$SI_{ij} = \begin{cases} 1 & \text{If event } i \text{ is unsafe according to associated threshold of perfomance indicator } j \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

The present study aims to investigate the differences between safety performance indicators in explaining the risk. This will be conducted via three phases. Firstly, the total unsafe events based on different indicators within the day are determined and the indicators' similarities are investigated in terms of equalities of the conflicts they have detected.

Analysis of risky events in total 24-hr duration contains no information about temporal distribution of unsafe events over the day. Thus, in the second phase, the day is divided into shorter 15-min intervals and Rear-end Collision Risk Index by each indicator is calculated within each interval (Equation 10).

$$RCRI_j = \frac{\sum_i^N SI_{ij}}{N} \quad (10)$$

In this equation SI is Safety Index (as defined in Equation 9) by each indicator j and N is the total number of events in that time interval.

Finally, to illustrate the indicators' differences in a more understandable way, Fuzzy C-Means method is employed to categorize each 15-min risk value by each indicator, into clusters. In Fuzzy algorithms of Clustering, a point may belong to all clusters at the same

Table 1- Performance indicators and their thresholds

Performance indicator	Symbol	Assumptions	Safety requirement (Threshold)
Time Headway	H	N/A	More than 2 s
Time to Collision	TTC	Following vehicle is driving faster than leading vehicle	More than 1.5 s
Proportional Stopping Distance	PSD	A Fixed Deceleration Rate of 3.4m/s² for the following vehicle	More than 1
Deceleration Rate to Avoid Collision	DRAC1	A Fixed Deceleration Rate for the following vehicle	Less than 3.4m/s²
	DRAC2	Maximum Available Deceleration Rate (MADR) follows Truncated Normal Distribution* for the following vehicles	Less than MADR
Stopping Distance Index	SDI1	Fixed Deceleration Rate of 3.4m/s² available for both Following and Leading Vehicles. A 2.5 s is considered for Perception Reaction Time	Equal to 0
	SDI2	Maximum Available Deceleration Rate for Following Vehicle follows Truncated Normal Distribution*. Upper limit of this distribution is assumed for the leading vehicles and a 2.5 s is considered for Perception Reaction Time	

* Average of 4.23 m/s², standard deviation of 0.71 m/s² and upper and lower limits of 6.34 m/s² and 2.12 m/s², respectively have been proposed for the assumed truncated normal distribution function.
N/A: Not applicable

time, with different degrees of membership [32]. To defuzzify, each 15-min risk value is assumed to belong to the category (level) with the highest degree of membership in this study.

Average difference of risk levels between the performance indicators is also calculated for each pair of indicators, using Equation 12.

$$\bar{D}_{ij} = \frac{\sum_{k=1}^{N} \left| Z_{ki} - Z_{kj} \right|}{N} \qquad (12)$$

where:

$\bar{D}_{ij}$ – Average difference of risk levels between safety performance indicators i and j in analysis period (24hr in this study);

Z_{ki} – Ordinal number of category (Low=1, Medium=2 and High=3) in clustering risk values associated to i^{th} performance indicator in k^{th} time interval;

N – Total number of time interval (N=96).

5. RESULTS

5.1 Analysis of unsafe events frequencies

Analysis of 24-hr traffic data (including 6,656 following events) shows that different performance indicators detected different number of following events as conflicts (Table 2). As the table shows, SDI detects a considerable number of conflicts in traffic stream, while DRAC, TTC and PSD are strict and H is rather moderate criteria in detecting unsafe events.

Furthermore, the intersections of sets including unsafe events based on different performance indicators have been analyzed. Since each event can be either safe or unsafe based on each of the seven performance indicators, each event belongs to the potential 128 ($= 2^7$) partitions (clusters) theoretically; however, only a few were observed to be available in practice.

Frequency analysis by partition resulted in 15 nonempty (i.e. with at least one member) clusters (C1 to C15) as depicted in Table 3. These findings were also supported by a K-Means clustering method conducted on the seven sets. In front of each cluster, there are cells that show the safety state of all members in that cluster according to safety performance indicators. Each cell has the value of 0 if all events in that cluster are safe based on the corresponding safety indicator and 1 if they are all detected as conflicts. The total number of events in each cluster is also shown in the last column. For example according to Table 3, ten events (out of 6,656) are unsafe according to all seven indicators (Cluster C3) and a total of 4,812 events have been detected as safe according to all indicators (Cluster C1).

Table 2 – Frequencies of unsafe events for different safety performance indicators

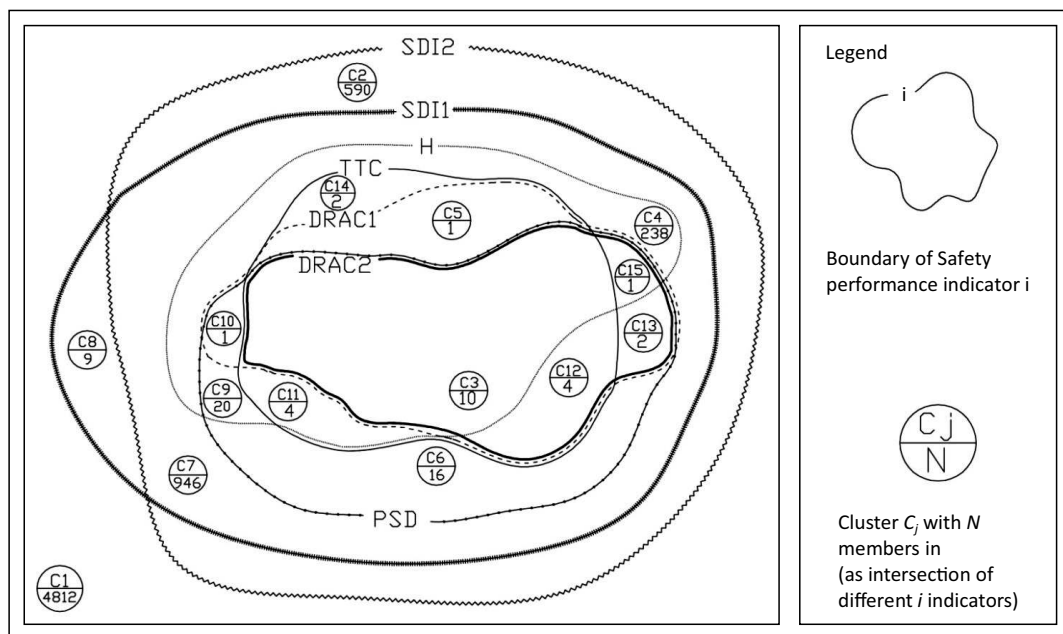| Frequency	Performance Indicator						
	H	TTC	PSD	DRAC1	DRAC2	SDI1	SDI2
Absolute	277	21	58	19	17	1,254	1,835
Relative (%)	4.2	0.3	0.9	0.3	0.3	18.8	27.6

Figure 1 – Schematic Venn-like illustration of events' clustering into unsafe sets

Table 3 – Events' clustering results based on frequency analysis*

Cluster Name	Safety Performance Indicator							Number of Members
	H	TTC	PSD	DRAC1	DRAC2	SDI1	SDI2	
C1	0	0	0	0	0	0	0	4812
C2	0	0	0	0	0	0	1	590
C3	1	1	1	1	1	1	1	10
C4	1	0	0	0	0	1	1	238
C5	1	1	0	1	0	1	1	1
C6	0	0	1	0	0	1	1	16
C7	0	0	0	0	0	1	1	946
C8	0	0	0	0	0	1	0	9
C9	1	0	1	0	0	1	1	20
C10	1	0	1	1	0	1	1	1
C11	1	1	1	0	0	1	1	4
C12	0	1	1	1	1	1	1	4
C13	0	0	1	1	1	1	1	2
C14	1	1	0	0	0	1	1	2
C15	1	0	1	1	1	1	1	1

* 15 Non-empty observed clusters from among 128 (=2^7) potential clusters.

The corresponding graphical illustration (unique in this problem) generated based on set theory and Venn-diagram concepts shows these 15 clusters as partitions (no common members) of the events' universe. A schematic illustration of clusters shown in *Figure 1* represents a Venn diagram with boundaries in accordance with the conditions shown in *Table 3*. Each closed curve in this Figure represents a performance indicator and the codes inside denote the name and number of members for each cluster. As the Figure shows, both SDI1 and SDI2 are very conservative indicators because almost all other clusters are subsets of SDI1 and SDI2.

5.2 Rear-end collision risk analysis

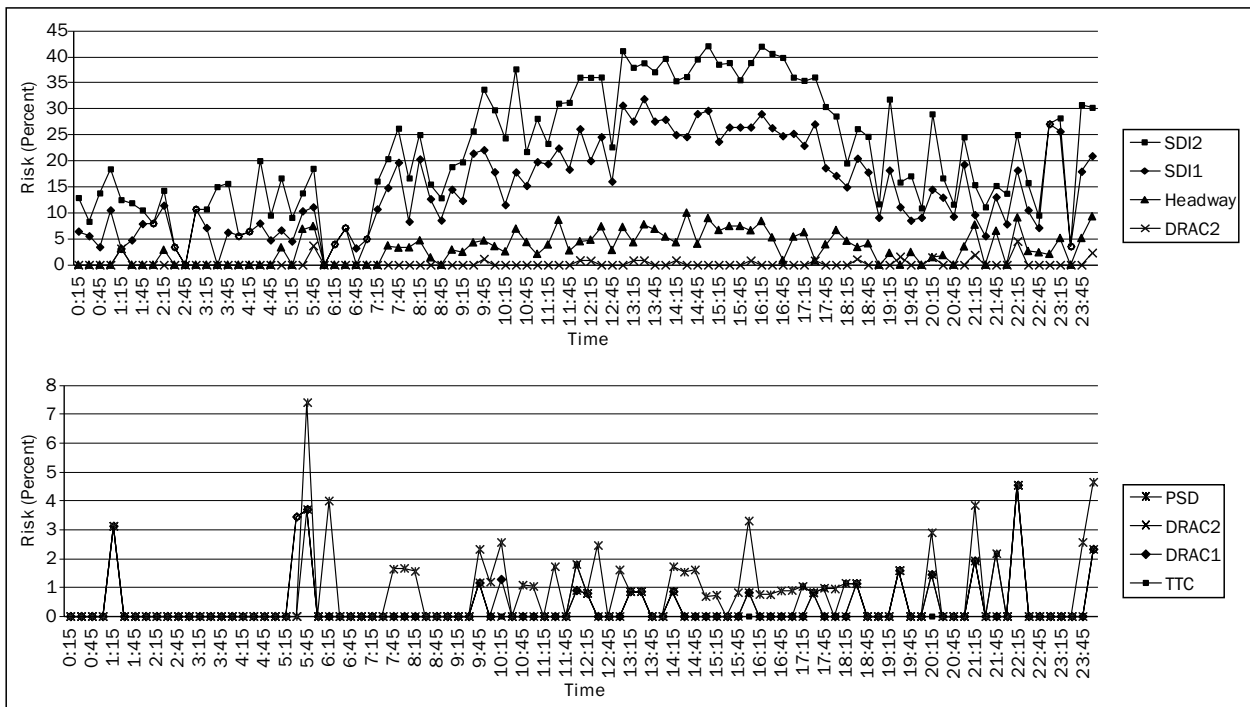The risk of a rear-end collision for each time interval may be calculated by each safety performance in-

Figure 2 – Comparison of risk of rear-end collision during the 24 hr based on different indicators (Analysis Interval=15 minutes)

Table 4 – Risk levels at 15min time intervals associated with different performance indicators

Time Interval	Safety Performance Indicator							Time Interval	Safety Performance Indicator						
	H	TTC	PSD	DRAC1	DRAC12	SDI1	SDI2		H	TTC	PSD	DRAC1	DRAC12	SDI1	SDI2
00:00-00:15	1	1	1	1	1	1	1	12:00-12:15	2	2	2	2	2	2	3
00:15-00:30	1	1	1	1	1	1	1	12:15-12:30	3	1	2	1	1	3	3
00:30-00:45	1	1	1	1	1	1	1	12:30-12:45	2	1	1	1	1	2	2
00:45-01:00	1	1	1	1	1	1	2	12:45-13:00	3	1	2	1	1	3	3
01:00-01:15	2	3	3	3	3	1	1	13:00-13:15	2	2	2	2	2	3	3
01:15-01:30	1	1	1	1	1	1	1	13:15-13:30	3	2	2	2	2	3	3
01:30-01:45	1	1	1	1	1	1	1	13:30-13:45	3	1	1	1	1	3	3
01:45-02:00	1	1	1	1	1	1	1	13:45-14:00	2	1	1	1	1	3	3
02:00-02:15	2	1	1	1	1	1	1	14:00-14:15	2	2	2	2	2	3	3
02:15-02:30	1	1	1	1	1	1	1	14:15-14:30	3	1	2	1	1	3	3
02:30-02:45	1	1	1	1	1	1	1	14:30-14:45	2	1	2	1	1	3	3
02:45-03:00	1	1	1	1	1	1	1	14:45-15:00	3	1	1	1	1	3	3
03:00-03:15	1	1	1	1	1	1	1	15:00-15:15	3	1	1	1	1	3	3
03:15-03:30	1	1	1	1	1	1	1	15:15-15:30	3	1	1	1	1	3	3
03:30-03:45	1	1	1	1	1	1	1	15:30-15:45	3	1	2	1	1	3	3
03:45-04:00	1	1	1	1	1	1	1	15:45-16:00	3	1	3	2	2	3	3
04:00-04:15	1	1	1	1	1	1	1	16:00-16:15	3	1	2	1	1	3	3
04:15-04:30	1	1	1	1	1	1	2	16:15-16:30	2	1	2	1	1	3	3
04:30-04:45	1	1	1	1	1	1	1	16:30-16:45	1	1	2	1	1	3	3
04:45-05:00	2	1	1	1	1	1	2	16:45-17:00	2	1	2	1	1	3	3
05:00-05:15	1	1	1	1	1	1	1	17:00-17:15	3	2	2	1	1	3	3
05:15-05:30	3	3	1	3	1	1	1	17:15-17:30	1	2	2	2	2	3	3
05:30-05:45	3	3	3	3	3	1	2	17:30-17:45	2	2	2	1	1	2	3
05:45-06:00	1	1	1	1	1	1	1	17:45-18:00	3	1	2	1	1	2	2
06:00-06:15	1	1	3	1	1	1	1	18:00-18:15	2	2	2	1	1	2	2
06:15-06:30	1	1	1	1	1	1	1	18:15-18:30	2	2	2	2	2	2	2
06:30-06:45	1	1	1	1	1	1	1	18:30-18:45	2	1	1	1	1	2	2
06:45-07:00	1	1	1	1	1	1	1	18:45-19:00	1	1	1	1	1	1	1
07:00-07:15	1	1	1	1	1	1	1	19:00-19:15	2	1	1	1	1	2	3
07:15-07:30	2	1	1	1	1	2	2	19:15-19:30		2	2	2	2		
07:30-07:45	2	1	2	1	1	2	2	19:30-19:45	2	1	1	1	1	1	2
07:45-08:00	2	1	2	1	1	1	2	19:45-20:00	1	1	1	1	1	1	1
08:00-08:15	2	1	2	1	1	2	2	20:00-20:15	1	1	3	2	2	2	2
08:15-08:30	1	1	1	1	1	2	1	20:15-20:30	1	1	1	1	1	2	2
08:30-08:45	1	1	1	1	1	1	1	20:30-20:45	1	1	1	1	1	1	1
08:45-09:00	2	1	1	1	1	2	2	20:45-21:00	2	1	1	1	1	2	2
09:00-09:15	2	1	1	1	1	2	2	21:00-21:15	3	2	3	2	2	1	1
09:15-09:30	2	1	1	1	1	2	2	21:15-21:30	1	1	1	1	1	1	1
09:30-09:45	2	2	2	2	2	3	3	21:30-21:45	3	2	2	1	1	2	1
09:45-10:00	2	1	2	1	1	2	2	21:45-22:00	1	1	1	1	1	1	1
10:00-10:15	2	1	2	2	1	1	2	22:00-22:15	3	3	3	3	3	2	2
10:15-10:30	3	1	1	1	1	2	3	22:15-22:30	2	1	1	1	1	1	1
10:30-10:45	2	1	2	1	1	2	2	22:30-22:45	2	1	1	1	1	1	1
10:45-11:00	2	1	2	1	1	2	2	22:45-23:00	2	1	1	1	1	3	2
11:00-11:15	2	1	1	1	1	2	2	23:00-23:15	2	1	1	1	1	3	2
11:15-11:30	3	1	2	1	1	3	3	23:15-23:30	1	1	1	1	1	1	1
11:30-11:45	2	1	1	1	1	2	3	23:30-23:45	2	1	2	1	1	2	3
11:45-12:00	2	2	2	2	2	3	3	23:45-00:00	3	2	3	2	2	2	3
Risk level		1 (Low)				2 (Medium)				3 (High)					

Table 5- Average differences of risk levels between performance indicators

	H	TTC	PSD	DRAC1	DRAC2	SDI1	SDI2
H	0	0.66	0.50	0.69	0.72	0.38	0.35
TTC		0	0.30	0.07	0.08	0.76	0.86
PSD			0	0.31	0.30	0.60	0.65
DRAC1				0	0.03	0.80	0.85
DRAC2					0	0.76	0.84
SDI1						0	0.19
SDI2							0

dicator as the ratio of the number of conflicts detected by that indicator to the total traffic volume obtained from ILDs (Equation 10). Using the 24-hr traffic data and considering analysis time intervals equal to 15 min (as a common time span in regular traffic studies), a plot of 96 points of risk values for each indicator over time can be drawn as depicted in *Figure 2*. As shown, the calculated risk values based on DRAC1, DRAC2 and TTC are very similar and considerably lower than other indicators.

Risk values denote the distribution of conflicts over the day and can be used (in their normalized form) as means for comparing different performance indicators.

$$u_{jk} = \frac{x_{jk} - x_{j\min}}{x_{j\max} - x_{j\min}} \qquad (11)$$

where u_{jk} and x_{jk} are the normalized and calculated risk of rear-end collision in the kth 15-min time interval according to safety performance indicator j, respectively. $x_{j\min}$ and $x_{j\max}$ are also the minimum and maximum risk values calculated within all 15-min time intervals according to safety performance indicator j, respectively.

Based on pair-wise t-test of average daily values of risk, the null hypotheses (the difference between the means for corresponding risk values is zero) is rejected at 5% significance level for all pairs of indicators except for DRAC1-DRAC2, DRAC2-TTC and TTC-DRAC1 (i.e. DRAC1, DRAC2 and TTC daily means represent the same values).

5.3 Analysis of risk levels

To more tangibly recognize the differences between safety performance indicators, the 15-min normalized risk values are categorized into clusters. Applying a two step analysis assuming a log likelihood distance measure and Schwarz's Bayesian Criterion (BIC) [33] on all risk values, optimal number of clusters is three for all safety performance indicators. Fuzzy C-Means (FCM) clustering of the risk values associated with all time intervals and indicators into three levels ("High", "Medium" and "Low" risk categories) are shown in *Table 4*. Each risk level in this Table is also represented by a colour ranging from light (Lower Risks) to dark (Higher Risks).

As depicted, the risk levels explained by some indicators are totally different from others. *Table 5* summarizes the $\bar{D}$ values drawn from Equation 12, for all pairs of indicators. Greater values in this table represent greater differences between related indicators in explaining rear-end collision risk. Moreover, shaded cells represent the pairs with the highest difference of risk levels, during the 24hr study. For instance, indicator SDI1 shows that the risk level is 0.76 levels different as average, compared to DRAC2.

6. DISCUSSION

There is a wide variety of safety performance indicators suitable for detecting conflicts in car following events, each of which addresses safety from a special aspect of kinematics. Empirically investigating the similarities between the indicators is of interest because it is not usually possible to find decisive mechanical relationships between them. The present study focused on indicators measurable by the ILD captured data in a freeway cross section, namely: time headway, Time to collision, proportion of stopping distance, deceleration rate to avoid collision (assuming that the available deceleration rate for the following vehicle follows a uniform and a truncated normal distribution, separately) and stopping distance index (with the same so called assumptions). This research advocates the hypothesis that while a given interaction between two successive vehicles in a car following event is assessed to be safe in terms of a variety of performance indicators, it may be recognized as being risky according to the others.

Analysis of frequencies of unsafe events according to safety performance indicators showed that the number of unsafe events detected during the 24-hr study is very different across different indicators (ranging from 0.3% of total events for DRAC1 and DRAC2 to more than 27% for SDI2). Unsafe events associated with all indicators are also unsafe according to both SDI1 and SDI2. In contrast there are a lot of events detected as unsafe according to stopping distance index while they are still safe based on all other indicators. This means that compared to other indicators, stopping distance index may be regarded as a considerably more conservative safety performance indicator.

Contrary to SDI, DRAC is not sensitive to the function of distribution assumed for the available deceleration rate for the following vehicles; all unsafe events associated with DRAC2 are also unsafe based on DRAC1. Moreover, almost all unsafe events based on both DRACs are still unsafe based on TTC. So TTC and DRAC explain the events' safety, very similarly. This implies that less TTC in freeway requires more deceleration rate to avoid a rear-end collision. On the other hand in almost all cases where a vehicle following a slower moving vehicle needs harsh braking to avoid the collision, the time to collision is also less than the critical threshold.

Analyses indicate that there are many high-risk events according to headway which are not considered as risky based on TTC. This means that there have been many occasions in which headways are less than the threshold, but their time to collision is still sufficient to avoid a collision. Such cases mainly include those where the speed of the following vehicle is less than or equal to the speed of the leading vehicle.

In contrast almost all occasions when the event is not safe according to TTC, it may be regarded as a conflict based on headway. This implies that in almost all cases, less time to collision corresponds to less time headways. A similar condition can be observed in comparing TTC and PSD; most risky events based on TTC, are still conflicts detected by PSD.

It is worth noting that the findings imply that indicators showing considerably high frequencies of conflicts (SDI and headway) may be weakly correlated with real collisions, mainly because there may exist additional options for the road users, such as Braking of the following vehicle to avoid collision with the leading vehicle, to avoid a collision. Thus, it can be argued that it is more difficult to predict the final outcome (crash) based on more conservative indicators.

Findings obtained from the frequency analysis of conflicts associated with different indicators, are also supported by rear-end collision risk analysis. Results indicate that the measured risk values associated with SDI are considerably higher in almost all consecutive 15-min time intervals compared to other indicators. Moreover, normalized values of risk associated with DRAC1, DRAC2 and TTC are not statistically different at a 95% confidence interval. This verifies that these indicators explain the rear-end collision risk in a very similar pattern.

Categorizing the normalized risks calculated in 15-min intervals into ordinal clusters (to address the situation from a safety perspective) supports the same patterns of findings. Compared to other indicators, considerably longer time intervals are shown to be in the most critical situation, if SDI is used to measure the rear-end collision risk. DRAC and TTC also show very similar risk clusters during the conduct of the analysis.

7. CONCLUSION

Different safety performance indicators are usually applied in traffic conflict analyses. In this study the aim was to empirically investigate how different the safety performance indicators identify the conflicts in a traffic stream on a freeway section, under the uninterrupted flow. Safety performance indicators investigated in this study were limited to time headway, time to collision, proportion of stopping distance, deceleration rate to avoid collision and stopping distance index.

Analysis of empirical data indicated that SDI can be considered as the single most inclusive and conservative indicator compared to others; not only all conflicts associated with all other indicators are unsafe according to SDI, but also a relatively great share of safe following events according to other indicators are taken as conflicts according to SDI.

Risky events based on DRAC are not sensitive to the distribution function of available deceleration rate on the following vehicles. DRAC and TTC are very similar indicators; almost all risky events based on TTC are also risky based on DRAC (and vice versa).

Comparison between H and TTC showed that in almost all risky events associated with TTC, headway is less than the critical threshold. However, there are considerable conflicts associated with headway which are still safe according to TTC. Comparison of PSD and TTC also provided the same results as H and TTC; almost all risky events according to TTC are also risky associated with PSD.

Different safety performance indicators can be employed as controls in launching novel intelligent transportation systems aiming to convey the real-time collision risk levels to drivers (for instance via variable message signs). The present findings suggest that at a specific time, different risk levels may be expected to be provided as information to drivers, if different indicators are employed as controls. However, the risk levels that are being communicated by the system to the drivers are likely to have small effects on driving behaviour unless the risk message corresponds to the risk drivers perceive in the driving environment. Investigating the degree of correspondence between the indicated risk by each performance indicator and the drivers' subjective judgment regarding the existing rear-end collision risk at any occasion should be subject to analysis in future studies.

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خلاصه

تحلیل تطبیقی شاخص‌های عملکردی ایمنی بر مبنای داده‌های شناسگر حلقه القایی

تاکنون تداخلات جریان ترافیک بر اساس شاخص‌های عملکردی مختلفی تشخیص داده شده‌اند. این مطالعه تلاش دارد تا تفاوت‌های بین شاخص‌های مختلف در تشخیص تداخلات جلو به عقب و تعیین خطر برخورد در یک جریان غیرمنقطع را مورد بررسی قرار دهد. برای این منظور اطلاعات خرد 24 ساعته جریان ترافیک (شامل 6657 وسیله نقلیه) با استفاده از شناسگرهای حلقه القایی نصب شده در مقطعی از آزادراه بین‌شهری جمع‌آوری گردید. شاخص‌های عملکردی مختلف (سرفاصله زمانی (H)، زمان تا برخورد (TTC)، نسبت فاصله دید توقف (PSD)، نرخ شتاب کاهشی برای اجتناب از برخورد (DRAC) و شاخص فاصله توقف (SDI) برای اندازه‌گیری هر رخداد تعقیب به‌صورت دوحالتی (ایمن/ناایمن) به‌کار رفت. رخدادهای ناایمن مربوط به هر شاخص تشخیص و رخدادهای ناایمن مشترک از نظر شاخص‌های متفاوت شناسایی گردیدند. همچنین توزیع‌های زمانی خطرهای برخورد جلو به عقب از نظر انواع شاخص‌های بررسی شده در بازه‌های زمانی 15 دقیقه‌ای مقایسه شد. در نهایت مقادیر 15 دقیقه‌ای ریسک در سه رده (کم، متوسط و زیاد) دسته‌بندی گردید. تکنیک‌های داده‌کاوی و روش‌های آماری نشان دادند که در حالی‌که SDI محافظه‌کارترین شاخص عملکردی ایمنی است، DRAC و TTC تعداد کمی از رخدادهای مشابه را ناایمن توصیف می‌کنند. تعداد معتنابهی از رخدادهای ناایمن بر اساس سرفاصله وجود دارند که هنوز از نظر TTC ایمن هستند. مقایسه PSD و TTC نیز نشان می‌دهد که تقریباً تمامی تداخلات مربوط به TTC بر اساس PSD نیز ناایمن هستند.

کلمات کلیدی

شاخص‌های عملکردی ایمنی، سرفاصله، زمان تا برخورد، فاصله توقف، تداخل، شناسگر حلقه القایی

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