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In search of the severity dimension of traffic events: Extended Delta-V as a traffic conflict indicator

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ABSTRACT

Most existing traffic conflict indicators do not sufficiently take into account the severity of the injuries resulting from a collision had it occurred. Thus far, most of the indicators that have been developed express the severity of a traffic encounter as their proximity to a collision in terms of time or space.

This paper presents the theoretical framework and the first implementation of Extended Delta-V as a measure of traffic conflict severity in site-based observations. It is derived from the concept of Delta-V as it is applied in crash reconstructions, which refers to the change of velocity experienced by a road user during a crash. The concept of Delta-V is recognised as an important predictor of crash outcome severity.

The paper explains how the measure is operationalised within the context of traffic conflict observations. The Extended Delta-V traffic conflict measure integrates the proximity to a crash as well as the outcome severity in the event a crash would have taken place, which are both important dimensions in defining the severity of a traffic event. The results from a case study are presented in which a number of traffic conflict indicators are calculated for interactions between left turning vehicles and vehicles driving straight through a signalised intersection. The results suggest that the Extended Delta-V indicator seems to perform well at selecting the most severe traffic events. The paper discusses how the indicator overcomes a number of limitations of traditional measures of conflict severity. While this is a promising first step towards operationalising an improved measure of traffic conflict severity, additional research is needed to further develop and validate the indicator.

1. Introduction

Traditionally, road safety analyses have relied mostly on crash data as their primary data source. Crash data, however, have some well-known limitations from an analytical point of view. These limitations include their relatively low frequency, leading to statistical issues related to small data samples, (unevenly distributed) under-reporting of crashes and the limited information they provide on behavioural and environmental aspects of the crashes (Laureshyn et al., 2010; Svensson and Hydén, 2006; Tarko et al., 2009). These issues limit the possibilities for drawing inferences about the causality of the crashes and how they can be prevented in the future (Davis, 2004; Elvik, 2007; Hauer, 2010; Tarko, 2012).

Therefore, a number of researchers argue that road safety analyses can strongly benefit from reliable methods that utilise observable non-crash events as a surrogate or a complement to crashes (Laureshyn et al., 2010; Tarko et al., 2009). The idea behind this is that traffic can be seen as a number of elementary events that differ in their degree of severity (unsafety), and that a relationship exists between the frequency and the severity of the events (Svensson and Hydén, 2006). Different concepts describing this idea have emerged over the years. Hydén (1987) describes this relationship with a 'safety pyramid', where the base of the pyramid is formed by normal traffic encounters that are quite safe and frequent, while the tip of the pyramid contains the most severe events, such as crashes resulting in injuries or fatalities, that are highly infrequent. Other researchers, such as Glauz and Migletz (1980) and Svensson (1998), also consider the events of the lowest severity ('perfectly safe' events) to be quite rare, too. They state that it is the

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events of moderate severity that are most frequent, because road users aim at optimising their behaviour in respect to both safety and mobility. This explains the preference for encounters of moderate severity because accepting smaller gaps can lead to gains in travel time (Svensson, 1998). A common ground of all concepts is, however, that the less severe traffic events: *i*) are more frequent than crashes; and *ii*) have an interdependency with crashes that, once it is sufficiently understood, can be used to estimate risk and infer causes of traffic crashes without having to observe crashes themselves. There is, indeed, a bulk of literature suggesting that a strong correlation exists between the frequency of 'serious conflicts' (though defined in a variety of ways) and the frequency of crashes (Brown, 1994; El-Basyouny and Sayed, 2013; Hydén, 1987; Lord, 1996; Migletz et al., 1985; Sacchi et al., 2013).

The literature reveals that dozens of traffic conflict severity indicators have been developed over the past decades (Allen et al., 1978; Hayward, 1972; Kraay et al., 1986; Laureshyn et al., 2010; Minderhoud and Bovy, 2001; Zheng et al., 2014). Most of these indicators express the severity of a traffic encounter as its proximity to a crash in terms of time or space (Zheng et al., 2014). However, proximity to a crash is only one dimension of 'severity'. Intuitively, getting close to a collision that would likely have resulted in a slight touch should not be considered as severe as getting equally close to a collision that would likely have resulted in a severe injury. Therefore, the potential severity of the consequences in the event that a crash would have taken place needs to be taken into account in some way (Laureshyn et al., 2010). According to initiatives such as Vision Zero, policymakers and road designers should strive towards a traffic system without fatalities or serious injuries (Johansson, 2009). The primary goal of Vision Zero is, therefore, to avoid *severe* crashes, rather than *all* crashes. Thus, the traffic conflict severity calculated from an indicator should express the proximity to a serious/fatal injury rather than the proximity to a crash alone. Very few of the existing traffic conflict indicators and techniques take the outcome severity into account in some way. For example, the Swedish Traffic Conflict Technique (Hydén, 1987) uses both the proximity in time and the speed at which the conflict takes place, which indirectly reflects the possible consequences. The Dutch technique, DOCTOR (van der Horst and Kraay, 1986), and the Canadian Traffic Conflict Technique (Brown, 1994) use a subjective score for potential consequences that is added to the objective nearness-in-time indicator(s). However, these examples are exceptions and the ways they combine the probability of a collision and its consequences are not completely problem-free.

In order to develop a traffic conflict severity indicator that meets this suggested definition, three questions need to be addressed:

1) How can we measure the proximity of an encounter to a crash?
2) How can we measure the consequences in the event a crash would have taken place?
3) How can we weigh both elements together?

These three questions will be addressed in the following subsections.

2. Extended delta-V as a measure of traffic conflict severity

2.1. How to measure nearness-to-collision?

As indicated, the nearness to a collision has been studied extensively, since most traffic conflict indicators are exclusively based on some measure of proximity in time or space. From a methodological perspective, the time-based measures are preferred, since they are the result of a combination of road users' speeds and distances (Laureshyn et al., 2010). One of the most frequently used indicators in traffic conflict studies is Time-to-Collision (TTC). TTC is defined as 'the time until a collision between the vehicles would occur if they continued on their present course at their present rates' (Hayward, 1972). In the Swedish traffic conflict technique, the TTC value at the moment of the evasive action start (TA, Time-to-Accident) together with the driving speed define the severity of a traffic conflict (Hydén, 1987), while the minimum value of the Time-to-Collision (TTC_{min}) during an encounter is used as a part of the DOCTOR technique (van der Horst and Kraay, 1986). In many recent studies using automated traffic conflict observations (Autey et al., 2012; Ismail et al., 2010; Sayed et al., 2013), TTC_{min} has also been commonly used as a traffic conflict indicator.

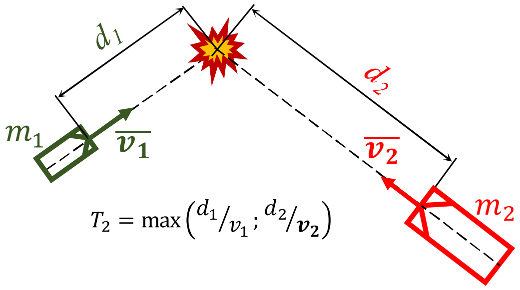


Fig. 1. Simplified illustration of the T_2 concept. Detailed calculations that take into account the dimensions of the road users can be found in Laureshyn et al. (2010).

Post-encroachment time (PET) is applicable in situations where two road users pass the 'conflict zone' with a time margin (Allen et al., 1978). It is defined as the time between the first road user leaving the 'conflict zone' and the second one arriving at it. A PET value equal to zero indicates no margin, i.e. a crash.

In order for a crash to take place, a collision course of the two road users is a pre-condition; without it, a collision is not possible. However, encounters without a collision course might have crash potential as well, since even minor changes in the spatial or temporal relationships between the road users can lead to a collision course. This means that the use of TTC alone is not sufficient for detecting all potentially dangerous situations. This is also supported by the observations of the actual conflicts in traffic (van der Horst, 1990). Svensson (1998) noticed that in situations where two vehicle drivers were about to miss each other by a very short time margin, their evasive behaviour was the same as if they were on a collision course. In other words, even though there was strictly speaking no collision course, the drivers perceived and acted as if they were on a collision course. Laureshyn et al. (2010), in an attempt of studying in detail the process of traffic conflicts, noted that an interaction between two road users could smoothly switch from being a collision course event to being a non-collision course event, and vice versa. Since this was a result of very minor (and reversible) speed changes, it appears counter-intuitive if the dangerousness of the situation would change dramatically from one time instance to the next. Also, it was noted that in fact the majority of the situations that a trained conflict observer would select as conflicts and having a collision course had in fact small time margins revealed if more accurate tools for speed and position measurements were used (Laureshyn et al., 2016).

Therefore, measures used to describe the severity of any interaction should be flexible enough to include both the collision course and non-collision course state, and allow a smooth transfer between both. The indicator T_2 suggested by Laureshyn et al. (2010) is an attempt to fill this gap. T_2 describes the expected time for the second (latest) road user to arrive at the conflict point, given unchanged speeds and 'planned' trajectories (see Fig. 1). If the road users are on a collision course, T_2 equals TTC. In the event that the two road users pass the conflict point with a time margin, T_2 reflects the maximum time available to take evasive actions and alleviate the severity of the situation. It is not stated in the original paper explicitly, but the current practice of the application of T_2 is that it is no longer calculated after the first road user has left the conflict zone (since the collision is no longer possible). This put a natural limit for how low a T_2 value can be reached during an interaction – for situations with a large time margin T_2 remains large, while when the margin is small T_2 can also reach small values.

The T_2 indicator extends the concept of TTC, since its calculation does not require a collision course, and therefore allows for a smooth transfer from collision-course and no-collision-course situations within the same interaction without a need to change indicators (unlike the traditional TTC versus PET dichotomy).

Similar to TTC, T_2 is a continuous indicator and can be calculated for any time instance as long as both road users are heading towards the common 'conflict area'. This raises the question of which value (or what combination of values) is most relevant and should be used. The latest possible value of T_2 during an interaction, i.e. the moment when the first road user leaves the 'conflict zone' and after which a collision is no longer possible without a change of trajectories, has practically the same meaning as the PET and reflects the moment when the two road users are closest in space to each other. Alternatively, the minimum value of T_2 (${T_2}^{min}$) during the encounter reflects the moment when they are closest in time. In most cases, these two values coincide (as T_2 normally decreases as the road users approach each other), but in the case of significant speed changes during an interaction, e.g. due to hard braking, they might represent different time instances.

Because of the more extensive scope of T_2 compared TTC, the T_2 indicator will be applied to express the nearness to a collision. More specifically, the minimum value of T_2 (${T_2}^{min}$) will be used, since this value represents the point where road users have approached each other closest in time, which can therefore be considered the most critical instant of their interaction.

2.2. How to measure consequences in the event a crash would have taken place?

Delta-V (Δv) is a notation often used in physics to denote an object's change of velocity (for example, because of an impact with another object). In the context of road crashes, Delta-V refers to the change of a velocity vector experienced by a road user during a crash. A rapid change in the magnitude and the direction of the speed implies extensive forces acting on the road user and can be expected to have a strong effect on personal injuries. Moreover, Delta-V is sensitive to the 'vulnerability' of the road user, since a light object colliding with a heavy one will 'bounce back', while the heavy object's speed will remain quite unchanged. This is a very important property in studies of crashes between, for instance, a car and a pedestrian or a heavy truck and a car.

Numerous examples in crash safety research support this assumption (Evans, 1994; Gabauer and Gabler, 2008; Johnson and Gabler, 2012). The relationship between Delta-V and the probability of a serious injury is visualised by a logistic regression curve in Fig. 2. The example is adopted from Gabauer and Gabler (2006), but the relationship between Delta-V and the risk of serious injury is confirmed by various authors (Augenstein et al., 2003; Evans, 1994; Gabauer and Gabler, 2008; Joksch, 1993; Ryb et al., 2007). Joksch (1993) defined a rule of thumb, showing that the mean rate of percentage of two-vehicle collisions resulting in a fatality is approximately proportional to Delta-V to the fourth power. Studies by Evans (1994) and O'Day and Flora (1982) confirm that Joksch's rule provides a good approximate fit.

Because of this strong evidence, various researchers consider Delta-V the best single predictor of crash severity (Evans, 1994; Shelby, 2011).

The estimation of Delta-V for crashes that have taken place is relatively straightforward. In these cases, there is a 'true' value of Delta-V that has taken place during the crash. Based on evidence about the post-collision trajectories of the involved road users and other information, such as vehicle specifications, experts can make a backward reconstruction of the pre-, during and post-collision phase. An estimation of the Delta-V values experienced by the vehicles in that particular crash can be calculated, for example, by using the momentum conservation principle (Burg and Moser, 2007).

It should be mentioned that an important characteristic of the collision which would affect the Delta-V values is how much energy is absorbed by the deformation of the colliding bodies, i.e. how 'elastic' the collision is. As a first simplified approach, we calculate Delta-V as if it was a completely inelastic collision, i.e. both objects stick together and move as one after the first contact. Delta-V (abso-

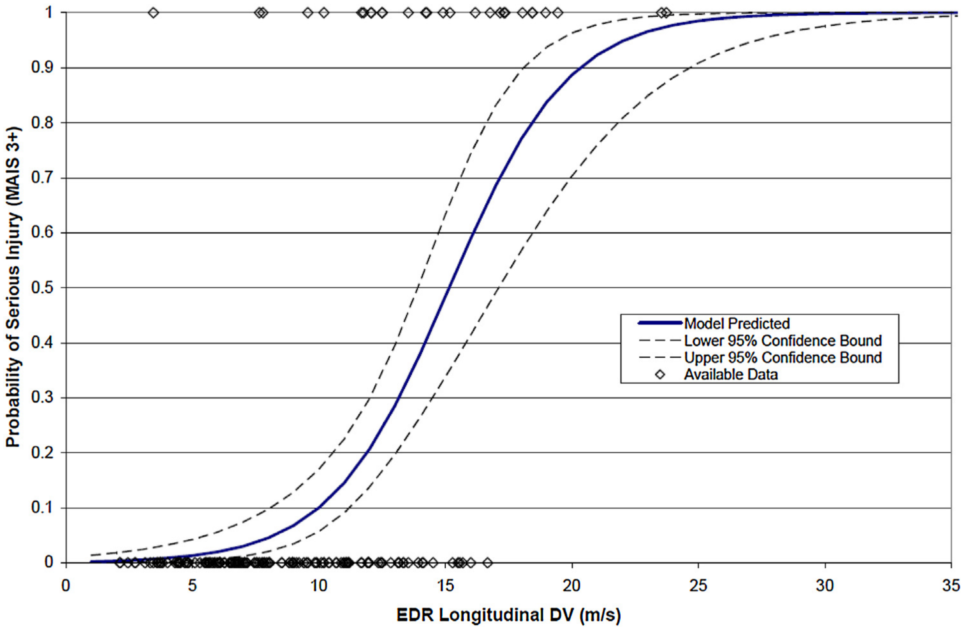


Fig. 2. Illustration of relationship between Delta-V and probability of a severe injury (Gabauer and Gabler, 2006).

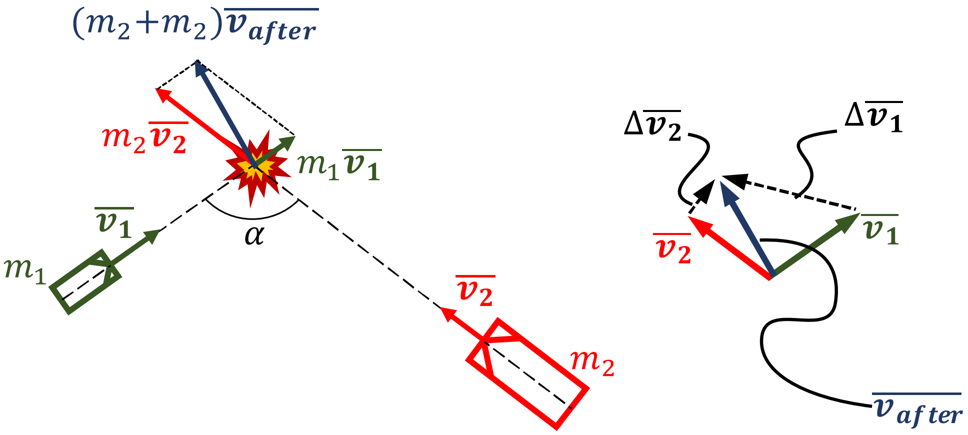


Fig. 3. Calculation of Delta-V based on momentum conservation principle (inelastic collision, i.e. two objects "stick together" after the first contact).

lute values) for two road users involved in an inelastic collision can be calculated (see Fig. 3):

$$\Delta v_1 = \frac{m_2}{m_1+m_2}\cdot\sqrt{v_1^2+v_2^2-2v_1v_2\cos\alpha} \quad \text{and}$$

$$\Delta v_2 = \frac{m_1}{m_1+m_2}\cdot\sqrt{v_1^2+v_2^2-2v_1v_2\cos\alpha}$$

where m_1, m_2–the masses of the road users 1 and 2 respectively,
v_1, v_2–their speeds,
α – the approach angle.

Since each road user has its own Delta-V value, to describe the interaction severity the highest value can be used.

The problem in applying this concept of Delta-V for traffic conflict studies is that no 'true' Delta-V value has manifested itself. However, when assumptions are made about the road users' future movements, it is possible to calculate a hypothetical or 'expected' Delta-V value that would have emerged from a crash. For example, assuming that both vehicles will crash with the same speed as they have at a certain moment during an interaction, their respective 'expected' Delta-V values can be estimated. This, however, creates a number of issues to resolve: *i*) the 'expected Delta-V' becomes a continuous variable that can be calculated for each instant during the interaction; and *ii*) for every instant during the interaction, different values can be calculated based on the assumptions that are made about how the interaction will develop (primarily, if the planned paths and speed will stay the same or change).

Delta-V has not been applied as a traffic conflict indicator until recently when it was incorporated into the automated conflict analysis algorithms of the Surrogate Safety Assessment Model (SSAM) (Gettman et al., 2008; Shelby, 2011). It is measured by calculating the expected change in velocity between the pre- and post-crash phase of the road users involved in the conflict assuming a hypothetical collision of the two road users at the angle and velocity they have at the moment TTC_{min} takes place. However, this approach has a number of limitations, particularly when applied on trajectory data observed in field rather than generated by a microscopic model. Firstly, the use of TTC_{min} as the time at which Delta-V is estimated limits its application to interactions in which there is a collision course only. As mentioned in the previous section, experience from field observation studies learns that many (even close) encounters in traffic do not have an actual collision course (Laureshyn et al., 2016; Svensson, 1998). Secondly, in this form, the indicator only represents the potential outcome severity in the event an accident would have taken place, but it does not include the nearness to a collision. An event with a large TTC_{min} value of several seconds can therefore have the same calculated value as a very close interaction with a TTC_{min} less than one second. Because of this, it is less suitable as a stand-alone indicator to distinguish severe from non-severe events in traffic. It has been acknowledged that the implementation of Delta-V in SSAM still needs substantial improvements (Shelby, 2011) and leads to some counter-intuitive results in experiments (Zha et al., 2014).

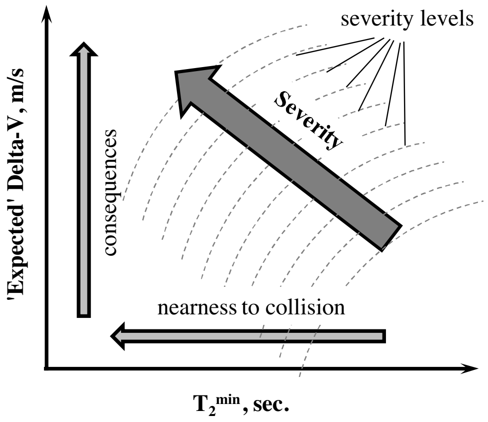
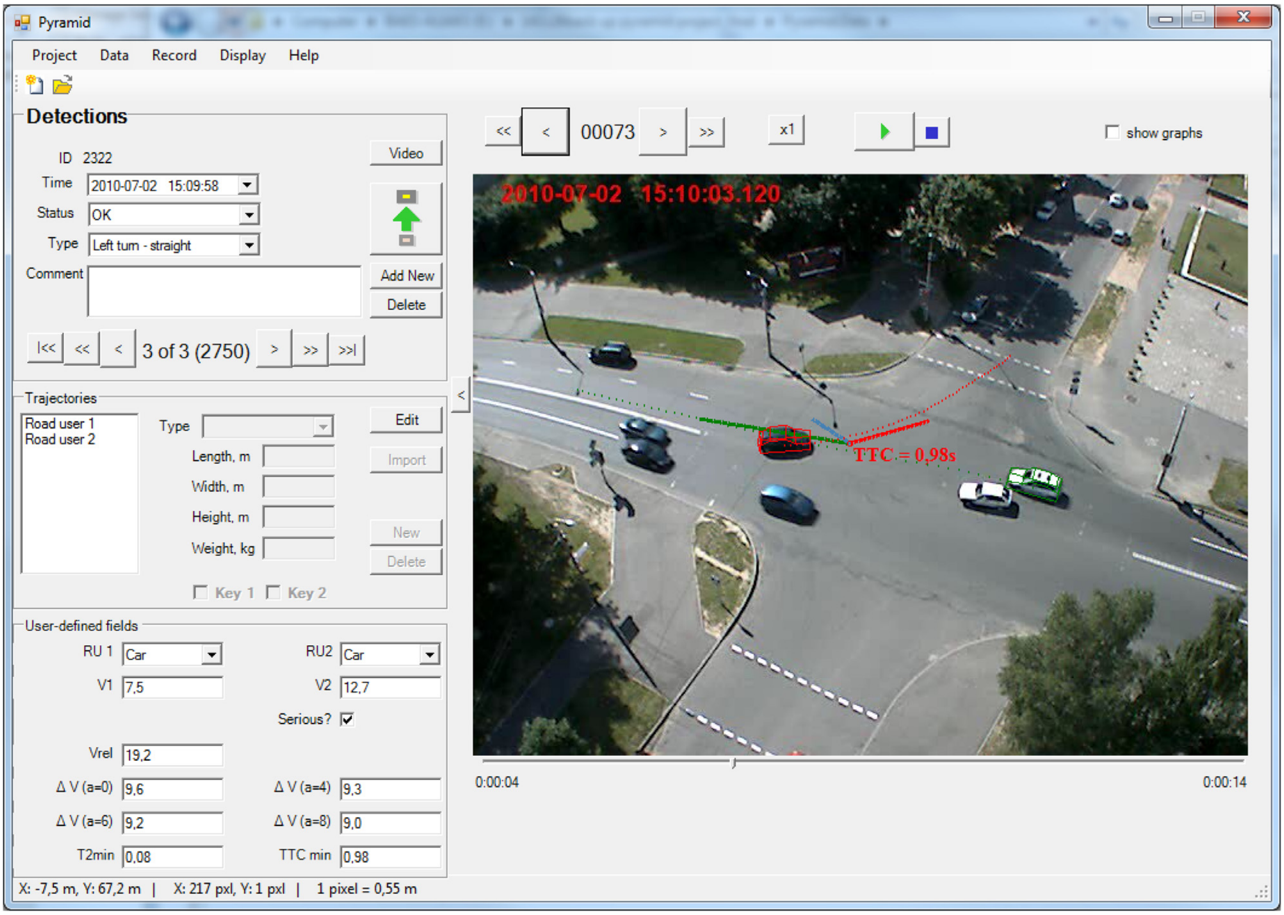


Fig. 4. Conceptual illustration of the main dimensions of conflict severity.

A framework that extends to non-collision course events is therefore to be preferred. The use of T_2^{min} instead of TTC_{min} as the basis for expressing the nearness to a collision in our indicator overcomes this limitation. To overcome the second limitation, the nearness to a collision and the estimated severity of the outcome in the event an accident would have taken place should be weighed together into a single indicator.

2.3. *Extended delta-V – an attempt to weigh nearness and potential outcome severity*

Fig. 4 conceptually plots the two main dimensions of traffic conflict severity that have been identified in the previous sections (T_2^{min} and 'expected' Delta-V at the same time instant). Quite intuitively, the severity of an encounter increases as the T_2^{min} value goes down (as the road users are closer to a collision) and as the 'expected' Delta-V value goes up (as the consequences can be more severe). Encounters that combine a low T_2^{min} value and a high 'expected' Delta-V value can be considered very dangerous situations. The "severity level"-lines represent the events of "equal severity". How exactly the "severity" can be calculated requires clarifications.



ID 2322
Time 2010-07-02 15:09:58
Status OK
Type Left turn - straight
Comment
3 of 3 (2750)

Trajectories
Road user 1
Road user 2
Type
Length, m
Width, m
Height, m
Weight, kg
☐ Key 1 ☐ Key 2

User-defined fields
RU 1 Car
RU2 Car
V1 7,5
V2 12,7
Serious? ☑
Vrel 19,2
Δ V (a=0) 9,6
Δ V (a=4) 9,3
Δ V (a=6) 9,2
Δ V (a=8) 9,0
T2min 0,08
TTC min 0,98

00073
2010-07-02 15:10:03.120
TTC = 0,98s
0:00:04
0:00:14

X: -7,5 m, Y: 67,2 m | X: 217 pxl, Y: 1 pxl | 1 pixel = 0,55 m

Fig. 5. Screenshot T-Analyst (only one camera view shown).

The problem of the 'expected' Delta-V is that it assumes a crash at the current speeds of the involved road users and does not take into account any available opportunity to take an evasive action and decrease the consequences of the hypothetical collision. We suggest a new severity indicator – Extended Delta-V – that is calculated with speeds that are reduced based on the assumption that the two road users spent the time available to brake before arriving at the collision point. The final speed, v, is then calculated as

$$v = \begin{cases} v_0 - at, if(v_0 - at) \geq 0; \\ 0, if(v_0 - at) < 0, \end{cases}$$

where v_0 is the initial speed;

a is the assumed deceleration rate;

t – time remaining for the evasive manoeuvre.

The definition of the time available is quite straightforward in situations with a collision course; here, the current TTC value can be used. If there is no strict collision course, the two road users actually have different times until they arrive at the potential collision point. In this context, it is the time for the latest-to-arrive road user, i.e. T_2 indicator, that appears to be most relevant, as it is objectively the maximal available time until a collision may happen (in case the first road user would 'freeze' at the collision point).

One final point that needs to be addressed is the assumed deceleration of the involved road users. First of all, it depends on the behaviour of the involved road users. Will they brake in a normal way, or will they apply maximum braking force? In this paper, we will test two simplified deceleration assumptions as a first case study. We will apply a deceleration of 4 m/s^2 for normal braking, and a deceleration of 8 m/s^2 for emergency braking; the latter is a conservative value for maximum deceleration that nearly all automobiles can achieve (Burg and Moser, 2007). These traffic conflict measures will be referred to as Extended Delta-V_4 and Extended Delta-V_8, respectively. The base Delta-V values, assuming no braking, will be referred to as Delta-V_0.

3. The dataset used to illustrate the concept

As a first test case, an intersection in the city of Minsk (Belarus) was analysed for three full days (6 a.m. till 9 p.m.). The intersection is a four-leg intersection equipped with classic two-phase traffic lights. Video footage of two cameras, installed at a rooftop close to the intersection, was used for the analyses.

The videos were analysed using T-Analyst, a semi-automated video analysis tool developed at Lund University (T-Analyst, 2016). The software allows for manually setting up 3D models of road users in video images and projecting their position on real-world coordinates. In this way, the software allows manual tracking of road users in one or more camera views and the calculation of some safety indicators such as TTC, Time Advantage, T_2 and relative speed (Laureshyn et al., 2010). It allows for dealing with large numbers of detections in one database. Fig. 5 shows a screenshot of the programme.

For illustrative purposes, it was decided to focus only on situations with a left-turning vehicle approaching from the left-hand side in the camera view, and a straight-travelling vehicle coming from the right-hand side in the camera view. This provided a relatively large number of interactions for analysis, while most of the ambiguity in defining the 'planned' trajectories was avoided.

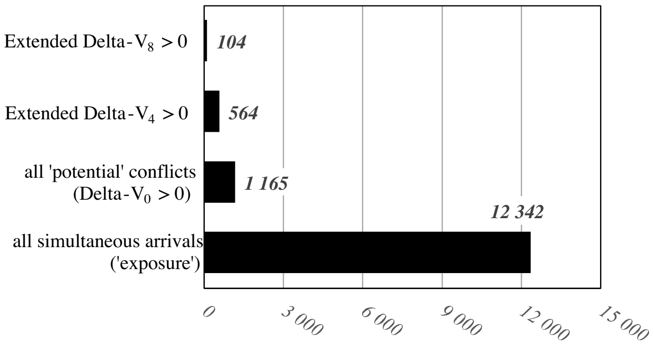


Fig. 6. Frequency of events by severity.

The two cameras' view allowed observing two approaching vehicles approximately 3–4 s before the potential conflict area. Simultaneous arrivals (situations of a vehicle intending to make a left-turn while there was a visible straight-travelling vehicle approaching) were counted as 'elementary exposure units' (Elvik et al., 2009). If the left turn was done in front of the straight-travelling vehicle, it was considered a 'potential conflict' and the trajectories for the two vehicles were extracted and analysed using T-Analyst. Free passages with no straight-travelling vehicle present were not considered 'exposure units' and were not included in the analyses.

4. Results

Three full days of observations resulted in a total exposure of 12,342 simultaneous arrivals. Of these simultaneous arrivals, 1165 involved a vehicle turning left in front of a vehicle driving straight through. For all of these situations, a non-zero Delta-V_0 value could be calculated. Of these 1165 situations, 564 had a non-zero Extended Delta-V_4 value and 104 had a non-zero Extended Delta-V_8 value. Extended Delta-V becomes zero in case both of the vehicles would come to a full stop before reaching the collision point if they had braked at the assumed deceleration rate (obviously, the higher a deceleration rate that is assumed, the earlier vehicles can stop and thus the more situations will have zero value of the Extended Delta-V). A clear safety hierarchy could be observed: events of low severity were much more common than events of higher severity (see Fig. 6).

All variables that have been collected for the records with non-zero Delta-V_0 values and their descriptive statistics are presented in Table 2.

The distribution of the Delta-V_0 values is shown in Fig. 7. The scatterplot in which the Delta-V_0 values are plotted against their corresponding T_2^{min} values does not show very clear patterns. The histogram shows a two-tailed bell curve, meaning that both the very low values and the very high values of Delta-V_0 are relatively uncommon.

The patterns become clearer when Extended Delta-V_4 and Extended Delta-V_8 are used to set the severity of the individual interactions (Fig. 8 and Fig. 9, respectively). Both histograms show a one-tailed shape with a high number of low values and a few high values. This pattern is a bit more distinct in the Extended Delta-V_8 histogram than in the Extended Delta-V_4 histogram.

The scatterplots shown in Fig. 8 and Fig. 9 are the same as the scatterplot of Delta-V_0 values (Fig. 7), but interactions with non-zero Extended Delta-V_4 and Extended Delta-V_8 values are highlighted in colour. The colour of these points provides the magnitude of the Extended Delta-V_4 and Extended Delta-V_8 values in a categorical way (increments of 2 m/s are chosen because they provide a suitable trade-off between accuracy and readability of the graphs). Also, the horizontal axis (T_2^{min}) has been adjusted to focus on the range in which these values occur to make the plot more readable. The dashed lines indicate the trend line of the selected Delta-V_0 versus T_2^{min} values (based on ordinary linear regression) for each category of the Extended Delta-V_4 and Extended Delta-V_8 values and may be seen as a first approximation of the "severity levels" conceptually introduced on Fig. 4 (we omit R^2 values and regression equations as the trend lines are based on a limited number of data points and their purpose is mainly illustrative).

The trend lines of higher categories of Extended Delta-V_4 and Extended Delta-V_8 values are positioned more to the top left of the graph than the trend lines of lower categories of Extended Delta-V_4 and Extended Delta-V_8. This shift towards the top left of the graph should be interpreted that generally events of higher severity correspond with higher values of Extended Delta-V_4 and Extended Delta-V_8. The graphs therefore show that both Extended Delta-V_4 and Extended Delta-V_8 identify quite well what can be believed to be the most dangerous conflicts from the dataset. The events of highest severity are a combination of high Delta-V_0 values and low T_2^{min} values and are, as mentioned earlier, assumed to be closest to a severe crash. While Extended Delta-V_4 leads to a higher number of selected events, it seems that Extended Delta-V_8 is more selective. Also, it is worth noting that the trend lines for Extended Delta-V_8 are steeper than for Extended Delta-V_4 which means that in weighing together the two dimensions of the severity more weight is given to T_2^{min}.

Table 1 shows the 20 most severe Extended Delta-V_8 situations, and how these situations rank for a number of other indicators. Quite some disagreement can be seen among the indicators. The most severe situation according to Extended Delta-V_8 is also considered the most severe situation according to TTC_{min} and T_2^{min}, while this situation is the second most severe situation according to Extended Delta-V_4. However, according to Extended Delta-V_0, this situation is only average; this results from the fact that it is a car–car situation (no differences in mass), with only a moderate relative speed. The extreme closeness in time most strongly defines the severity of this situation; a T_2^{min} of 0.08 s implies a very narrow miss. The value considered the second most severe by Extended Delta-V_8 is considered the most severe by Extended Delta-V_4. This situation has a rather high Delta-V_0 value, caused by a moderate relative speed in combination with a large difference in mass (car-HGV situation). There is, however, a slightly higher time margin that can still be used to brake, which explains the difference in ranking between the two Extended Delta-V indicators.

As a result of the difference in the assumed deceleration rate between Extended Delta-V_8 and Extended Delta-V_4, it can be seen that the Extended Delta-V_4 indicator places a bit more emphasis on the combination of the relative speed and the mass ratio of the situation, while the closeness in time is a much stronger determinant for the Extended Delta-V_8 situations.

In general, it can be seen that the closeness in time still highly defines the severity of an interaction. The 20 most severe situations according to Extended Delta-V_8 all have a T_2^{min} value of 1.5 s or lower, and all rank in the top 80 most severe situations according to T_2^{min}. A high closeness in time is, therefore, still an important prerequisite for an encounter to be considered severe by the Extended Delta-V indicators. This is an important characteristic from a theoretical point of view, since medium-severity time margins are not to be considered dangerous. Rather, they represent the normal traffic process where road users balance the need to behave sufficiently safe with the desire to maintain a sufficiently high level of mobility (Hydén, 1987; Laureshyn et al., 2010; Svensson and Hydén, 2006). On the other hand, a high Extended Delta-V_0 value is less essential to be considered a rather severe situation; as long as the time

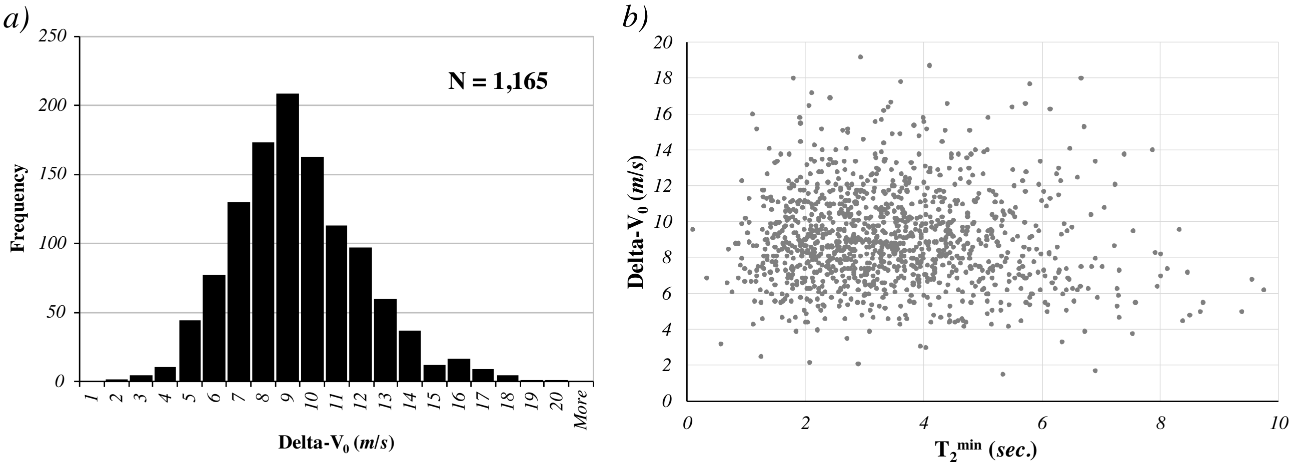


Fig. 7. Delta-V_0 values: *a*) histogram; *b*) scatterplot against T_2^{min}.*b*.

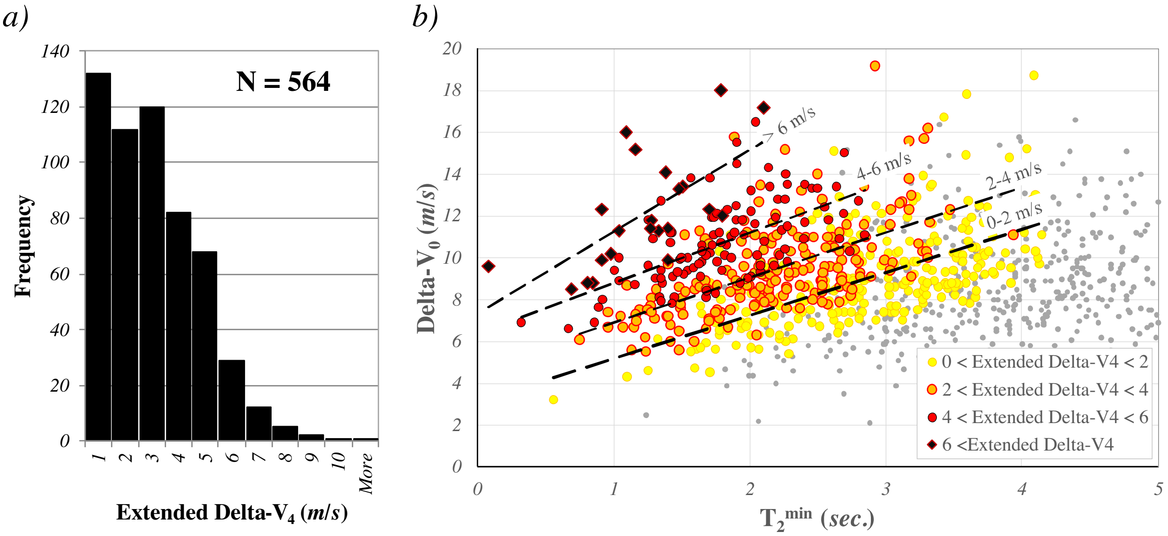


Fig. 8. Extended Delta-V_4 values: a) histogram; b) marked on Delta-V_0 scatterplot.

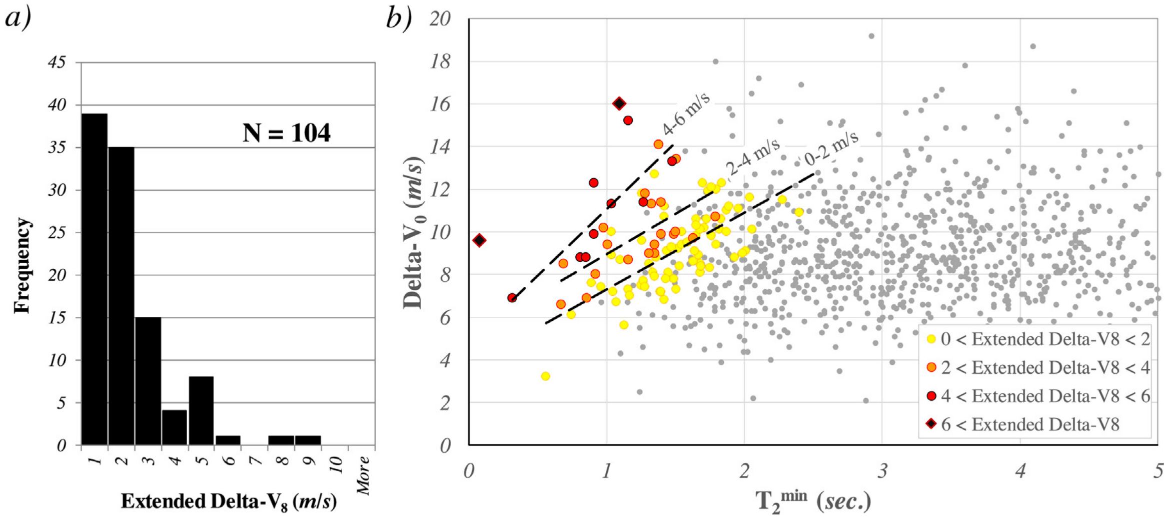


Fig. 9. Extended Delta-V_8 values: a) histogram; b) marked on Delta-V_0 scatterplot.

Table 1

Comparison ranking of the 20 most severe Extended Delta-V8 situations (“Extended Delta-V” is abbreviated to “ΔV”).

Rank ΔV_8	Value ΔV_8 (m/s)	Rank ΔV_4	Value ΔV_4 (m/s)	Rank ΔV_0	Value ΔV_0 (m/s)	Rank T_2^{min}	Value T_2^{min} (s)	Rank TTC_{min}	Value TTC_{min} (s)	Rank relative speed	Value relative speed (m/s)	Type of situation	mass ratio*
1	9	2	9.3	409	9.6	1	0.08	1	0.98	191	19.2	car-car	1.00
2	7.7	1	11.1	17	16	23	1.09	58	3.99	135	20.2	car-HGV	3.85
3	5.8	3	8.7	119	12.3	12	0.91	–	no value	577	15.5	car-HGV	3.85
4	5	7	7.6	202	11.3	19	1.04	35	3.42	293	18	car-minivan	1.69
5	4.7	24	5.8	908	6.9	2	0.32	12	2.87	741	14.1	car-car	1.00
6	4.5	8	7.3	194	11.4	40	1.27	–	no value	38	22.8	car-car	1.00
7	4.4	19	6.2	561	8.8	8	0.85	–	no value	327	17.7	car-car	1.00
8	4.3	17	6.3	561	8.8	7	0.81	–	no value	338	17.6	car-car	1.00
8	4.3	4	8.2	27	15.2	28	1.16	–	no value	390	17.2	car-HGV	3.85
10	4.2	11	6.9	367	9.9	11	0.91	9	2.29	154	19.8	car-car	1.00
10	4.2	6	7.8	75	13.3	72	1.48	–	no value	5	26.6	car-car	1.00
12	3.9	16	6.4	327	10.2	16	0.98	66	4.1	491	16.2	car-minivan	1.69
13	3.7	13	6.5	367	9.9	59	1.4	31	3.4	154	19.8	car-car	1.00
13	3.7	20	6.1	628	8.5	5	0.69	4	1.92	413	17	car-car	1.00
15	3.6	5	8	43	14.1	57	1.38	–	no value	327	17.7	car-HGV	3.85
16	3	14	6.5	202	11.3	49	1.33	–	no value	44	22.6	car-car	1.00
17	2.9	23	5.9	353	10	79	1.5	–	no value	146	20	car-car	1.00
17	2.9	31	5.5	516	9	47	1.31	14	2.91	293	18	car-car	1.00
17	2.9	15	6.4	194	11.4	59	1.4	–	no value	38	22.8	car-car	1.00
17	2.9	53	5	724	8	13	0.92	20	3.17	526	16	car-car	1.00

* Mass of the heaviest vehicle divided by the mass of the lightest vehic.

margin is small enough, moderate values of Delta-V_0 can also be considered situations of fairly high severity.

It is noteworthy that there is little correspondence between Extended Delta-V_8 and TTC_{min}. Many of the most severe Extended Delta-V_8 situations have no TTC value at all, i.e. there was no collision course. On the one hand, there is strong evidence for TTC to be related to the severity of the situation. For example, in a calibration study comparing the severity ranking of situations using different traffic conflict techniques, TTC_{min} was found to be a dominant component that the scores of all techniques correlated with (Grayson, 1984).[1] On the other hand, there might be advantages in including situations without a collision course, too. For example, the DOCTOR technique (van der Horst and Kraay, 1986) uses TTC_{min} as one of the main values to assess traffic conflict severity, but also considers close encounters without a collision course serious conflicts.

5. Discussion

5.1. Strengths and applications

The Extended Delta-V indicator builds on well-established concepts of crash reconstructions in order to represent the risk of serious injuries or fatalities as closely as possible (Augenstein et al., 2003; Evans, 1994; Gabauer and Gabler, 2008; Joksch, 1993; Ryb et al., 2007). Integrating the ‘Delta-V’ element with the time proximity to crashes adds a severity dimension to existing conflict indicators. As the biggest societal burden comes from crashes with the most severe outcomes, attempts to predict and prevent the highest level injuries have been at the core of traffic safety policy and research for a long time. Therefore, valid traffic conflict indicators should by nature be capable of predicting the most relevant crash scenarios, i.e. those with the most severe outcomes. Thus, adding a severity dimension to a conflict indicator might improve the validity of conflict indicators as predictors for crashes. Obviously, further assessment is needed to verify this.

Table 2

Descriptive statistics of the dataset.

Variable	Descriptive statistics (N = 1165)
Delta-V_0 (m/s)	None-zero values = 1165 Mean = 8.98; St. Dev. = 2.66; Min = 1.5; Max = 19.2
Extended Delta-V_4 (m/s)	None-zero values = 564 Mean = 2.56; St. Dev. = 1.79; Min = 0.1; Max = 11.1
Extended Delta-V_8 (m/s)	None-zero values = 104 Mean = 1.76; St. Dev. = 1.59; Min = 0.1; Max = 9.0
T_2^{min} (s)	Available values = 1163 Mean = 4.05; St. Dev. = 13.99; Min = 0.08; Max = 473.33
TTC_{min} (s)	Available values = 247 Mean = 5.19; St. Dev. = 2.38; Min = 0.98; Max = 32.83
Relative speed (m/s)	Mean = 15.5; St. Dev. = 3.96; Min = 3.1; Max = 29.9
Left-turning vehicle type	Available values = 1132 Car = 1024; Heavy goods vehicle (HGV) = 78; Bus = 0; Van = 62
Left-turning vehicle speed (m/s)	Mean = 5.35; St. Dev. = 1.79; Min = 0.4; Max = 12.9
Straight through vehicle type	Available values = 1132 Car = 844; HGV = 170; Bus = 56; Van = 94
Straight through vehicle speed (m/s)	Mean = 12.02; St. Dev. = 3.76; Min = 0.1; Max = 21.7

The Extended Delta-V indicator is sufficiently flexible to include collision course and non-collision course events, as well as crash and non-crash events. T_2 has been developed explicitly with the aim of allowing for the smooth transfer between collision-course and non-collision course events (Laureshyn et al., 2010). In the event of an actual crash, T_2^{min} becomes zero, and all variations of the Extended Delta-V values converge to the ‘true’ Delta-V value

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[1] One could speculate, however, about the accuracy of the measurements done in the calibration study. Even though the measurements were actually taken from videos, many factors, such as a simplified camera calibration model and calculation procedures for TTC, low resolution of the images, etc., could contribute to situations whereby very small time gaps are labelled as having a collision course.

experienced by the vehicles involved in the actual crash. This seems to make the indicator flexible enough to cover the whole spectrum of safety relevant situations, ranging from normal encounters over serious conflicts up to and including crashes. This is a major strength of the developed indicator, and it is an adaptation towards use in real-world observations (that often have no collision course) as well as an extension of the Delta-V concept as it has been implemented in microsimulation (Gettman et al., 2008).

A noticeable feature of the indicator is that the severity of some conflicts, those with high Extended Delta-V values, may be considered higher than the severity of some actual crashes. Imagine a collision between two cars manoeuvring at very low speeds in a parking lot. In this situation, the risk for a severe injury is low and the actual Delta-V values that take place during the crash are also low. On the other hand, a narrow miss between two vehicles with high differences in mass and speed is likely to have a much higher (calculated) Extended Delta-V value. Although there is no actual crash, the situation is still severe since the road users come very close to a situation with a high risk of serious injury. However, this does make sense if one's purpose is to assess the severity of a traffic situation, not only in terms of its proximity to a crash, but in terms of its closeness to a serious injury.

The suggested indicator can be used in fully automated traffic conflict analyses, since all required parameters (speeds, trajectories, road user type estimates) can be retrieved from video footage, and with slight alterations, also from data from other sensors. Given the rapid evolution of the traffic conflict observation domain towards automated analyses (Laureshyn et al., 2010; Saunier et al., 2010), this is an important advantage of the indicator.

5.2. Challenges and future research

For reasons of feasibility, this first operationalisation of the Extended Delta-V indicator accepted a number of simplified assumptions. Making them reflect realistic situations more closely should improve the performance of the indicator:

1) The assumed braking force is now a constant. The true maximum braking force, however, depends on the maximum tyre-roadway friction which, in turn, depends on the weather, the type and condition of the pavement, the vehicle type, the type and condition of the tyres, the speed of the vehicle, etc. (Roe et al., 1991; Warner et al., 1983). While it will not be feasible to include all of these aspects (for instance, video footage does not allow for retrieving information about the tyres of the vehicle), a number of refinements can be introduced;
2) While it is expected that Extended Delta-V will especially highlight vulnerable road user (VRU)-related conflicts, the evasive actions of pedestrians and cyclists are not the same as motor vehicles. For example, cyclists were found to swerve rather than brake (Laureshyn et al., 2016) while pedestrians have an ability to literally stop in a fraction of a second and even change direction to the opposite (jump back). Assumptions of 'a tyre braking on dry asphalt' are definitely not ideal here;
3) Only four different vehicle masses were distinguished (car, HGV, bus, minivan). These assumptions can be refined. Information about the mass of vehicles can usually be retrieved from various databases. For efficiency reasons, it would be best if the estimated mass of vehicles could be retrieved automatically by the video analysis software. One possibility could be to relate the mass of the vehicle to its length, which is a feature that can be retrieved automatically relatively easily;
4) In the current calculations, a completely inelastic collision is assumed. This can be seen as a collision between two clay balls, which will stick together after the point of collision and proceed along the same post-collision trajectory. While this is a reasonable approximation, in reality, motor vehicle crashes exhibit a somewhat elastic effect, where the vehicles slightly rebound off each other again (Shelby, 2011). This effect is modelled using a so-called coefficient of restitution, which equals zero (0.0) for completely inelastic collisions (as was assumed here), and one (1.0) for completely elastic collisions. In practice, low speed collisions have a coefficient of restitution of around 0.4, while this coefficient decreases at higher impact speeds to around 0.1 (Nordhoff, 2005);
5) It should be pointed out that, while there is a clear correlation between the (actual) Delta-V endured by a road user during a crash and the likelihood of (severe) injury, the relationship between crash impact and injury outcome is quite complex and the resulting severity of injuries from a crash are affected by many factors. For example, elderly vehicle occupants are more likely than younger occupants to be severely injured in similar crashes (Evans, 2001; Farmer et al., 1997; Li et al., 2003). The crashworthiness of a vehicle (including passive safety systems) also significantly affects the probability and severity of injuries in a given crash. Additionally, motor vehicles can absorb more impact energy in frontal impacts than in side impacts due to the presence of crumple zones in the front of the vehicle. Occupants who are seated more closely to the point of impact have a higher probability of sustaining severe injuries than occupants farther away from the impact point (Evans and Frick, 1988). While some of these aspects could be taken into account when further advancing the conflict indicator, others cannot.

Apart from optimising the theoretical framework and the parameters of the calculation, validation research is needed to check whether a traffic conflict indicator can be used as a true measure of safety. This implies that a sufficiently large body of evidence must be found, showing close correlations between crashes and conflicts. This need for validity research does not only apply to the Extended Delta-V indicator as it was introduced in this paper, but also to many of the indicators that are applied today (Laureshyn et al., 2016; Zheng et al., 2014).

While this paper shows that the applied Extended Delta-V indicators allow for ranking the severity of traffic encounters, it is not yet clear how the values should be interpreted from a safety perspective. For instance, it is unclear whether a border should be defined between what is considered a serious or a non-serious conflict, or that the results should be interpreted from a continuous perspective.

One of the approaches in surrogate safety analysis is the use of extreme value theory, i.e. calculations of probabilities to get very extreme (having low probability) values of an indicator based on the distribution of the 'normal' values (Songchitruksa and Tarko, 2006). For example, if the PET indicator is used, one could formulate the problem as 'what is the probability of observing $PET < 0$ s', which means a collision. While studying the Delta-Vs from actual collisions, one can find a threshold after which severe injuries become very probable; however, in the case of a hypothetical Extended Delta-V value, it is not clear how the threshold should be defined, and once defined, how it should be interpreted.

The case study only applied to one type of manoeuvre, one type of intersection, and only to motorised vehicles. It will be necessary to test the indicator in other circumstances and for other types of road users. It will be especially relevant to see how the indicator will behave when applied to situations with VRUs. Existing traffic conflict techniques are usually optimised for encounters among car drivers, but are often less suitable for applying to VRUs (Shbeeb, 2000).

6. Conclusions

We suggest Extended Delta-V as a measure of traffic conflict severity that takes into account both proximity to a crash and severity of its potential consequences. The indicator is applicable to situations in which two road users are heading towards a common conflict area. Extended Delta-V is calculated as the expected change of velocity experienced by a road user in the event that the conflict would have resulted in a crash. The relevant value is the one that applies to the moment T_2^{min} takes place, which is the moment when the expected time for the last-to-arrive road user to arrive at the common conflict point becomes minimal. A first case study suggests that the indicator succeeds quite well at integrating both dimensions of conflict severity and selecting the most severe events in traffic. While this is a promising first step towards operationalising an improved traffic conflict indicator, further research is needed on the development of the indicator itself as well as on the validity of selected events as predictors for the eventual safety level.

Declaimer

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