PERGAMON

Accident Analysis and Prevention 33 (2001) 89–97

ACCIDENT ANALYSIS & PREVENTION

www.elsevier.com/locate/aap

Extended time-to-collision measures for road traffic safety assessment

Michiel M. Minderhoud [1], Piet H.L. Bovy *

Delft University of Technology, Faculty of Civil Engineering and Geosciences, Traffic Engineering Section, PO Box 5048, NL-2600 GA Delft, The Netherlands

Received 7 July 1999; received in revised form 1 March 2000; accepted 7 March 2000

Abstract

This article describes two new safety indicators based on the time-to-collision notion suitable for comparative road traffic safety analyses. Such safety indicators can be applied in the comparison of a do-nothing case with an adapted situation, e.g. the introduction of intelligent driver support systems. In contrast to the classical time-to-collision value, measured at a cross section, the improved safety indicators use vehicle trajectories collected over a specific time horizon for a certain roadway segment to calculate the overall safety indicator value. Vehicle-specific indicator values as well as safety-critical probabilities can easily be determined from the developed safety measures. Application of the derived safety indicators is demonstrated for the assessment of the potential safety impacts of driver support systems from which it appears that some Autonomous Intelligent Cruise Control (AICC) designs are more safety-critical than the reference case without these systems. It is suggested that the indicator threshold value to be applied in the safety assessment has to be adapted when advanced AICC-systems with safe characteristics are introduced.

Keywords: Safety assessment; Time-to-collision; Autonomous intelligent cruise control

1. Introduction

Most car manufacturers are currently developing in-vehicle systems aimed at improving driver comfort, which possibly also may affect traffic flow characteristics as well as traffic safety. The traffic safety aspect is subject of this article. Recent technological developments in the field of driving task automation, such as the development and careful introduction of Autonomous Intelligent Cruise Control (AICC) or Collision Avoidance Systems, justify safety impact assessments. It is expected that the introduction of new vehicle technologies will have both positive and negative impacts on traffic safety.

We can distinguish direct safety benefits (such as enhanced driving performance and mitigation of crash consequences) and indirect safety benefits (e.g. reduced exposure, reduced driver stress and fatigue, reduced conflicts and variance in behavior). Also, direct safety risks (driver distraction, overload, reduced situation awareness) and indirect safety risks (behavioral adaptation, loss of skill, etc.) can be distinguished. Resulting impacts largely depend on the extent to which the support system meets drivers' needs and is compatible with human capabilities and limitations.

Since intelligent driver support systems are not yet widespread present in the car traffic flow, direct safety measures such as accident and fatality frequencies can not be obtained in many cases. Since empirical collection of accident data is not yet an option, other methods for safety assessment are needed.

Among these are ex ante assessments with which the safety consequences of different vehicle fleet compositions relative to a base (do-nothing) case can be estimated. To this end, microscopic simulation is a useful approach. With the application of microscopic simulation tools a variety of traffic safety indicators can be adopted, such as the headway distribution, time-to-col-

* Corresponding author. Tel.: +31-2781681; fax: +31-2783179.
E-mail addresses: mmm@hcg.nl (M.M. Minderhoud), bovy@ct.tudelft.nl (P.H.L. Bovy).
[1] Present address: Hague Consulting Group, Surinamestraat 4, NL-2585 GJ, The Hague, The Netherlands.

0001-4575/00/$ - see front matter
PII: S0001-4575(00)00019-1

lision (TTC) distribution, or number and severity of shock waves. The comparison of headway distributions at a cross-section gives an indication about the positive or negative shifts in traffic safety, assuming that small headways are relatively unsafe. Also, a comparison of time-to-collision distributions can be made to evaluate safety changes. Other safety indicators can be used as well, such as the number of shock waves (see e.g. VanArem and DeVos, 1997), time-to-accident (TTA), post-encroachment-time (PET), deceleration-to-safety-time (DTS) (see e.g. Hyden, 1996; Topp, 1998). Absolute safety effects are hard to derive with such comparative analyses. It may also be clear that traffic safety analyses with microscopic traffic simulation have a number of restrictions. Most important, driver behavior in real road traffic is more diverse and less predictable than can be implemented within a model. Generally, microscopic simulation models developed for traffic flow analyses require less detail with respect to driver errors modeling than required for safety analyses. Furthermore, microscopic simulation models mostly neglect parts of the lateral driving tasks, such as keeping the vehicle on the roadway. Despite these limitations, simulation can give valuable insights into relative changes of traffic flow safety. In many cases, it is the only way available in ex ante assessment of expected future conditions.

In assessing the safety impacts of future intelligent in-vehicle devices interacting with the driver, adequate safety indicators should be applied which express the level of safety into a comparative and understandable variable. Focus of this article is the specification and application of such new safety measures based on the time-to-collision notion. This implies that the lateral safety concerns are not taken into account. The time-to-collision indicator expresses only indirect safety concerns related to the execution of the longitudinal driving task which should be interpreted with this limitation in mind.

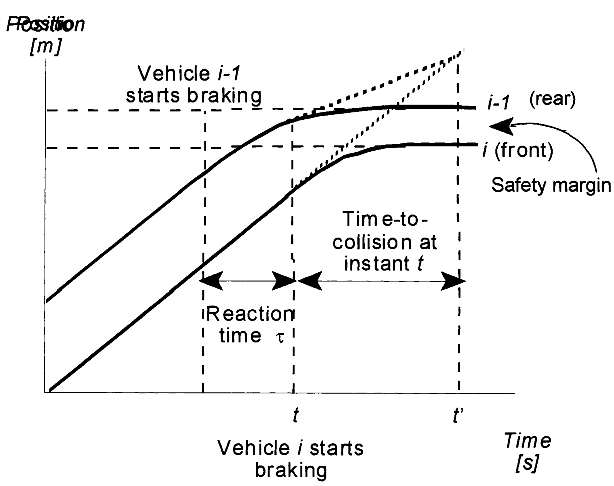

Fig. 1. Time-to-collision notion illustrated with vehicle trajectories.

Section 2 will introduce the time-to-collision notion followed by Sections 3 and 4 presenting refined indicators, respectively the TET (Time Exposed Time-to-collision indicator) and the TIT (Time Integrated Time-to-collision indicator). Calculation of these safety indicators is outlined in Section 5, followed by an example of application in Section 7. Section 8 gives a summary and some implications of the investigation. The presented safety indicators are especially (but not exclusively) suited for application in microscopic simulation studies of traffic, in which much more information is available about individual vehicle movements than usually is the case in empirical studies.

2. Time-to-collision notion

2.1. Definition

The time-to-collision notion has been applied beneficially as a safety indicator in safety analyses. The time-to-collision (TTC) concept was introduced in 1971 by the US researcher Hayward. A TTC value at an instant t is defined as *the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained*, see e.g. Hyden (1996). The time-to-collision distribution has been applied in several studies to identify traffic safety impacts (among others Fancher et al., 1997; VanArem and DeVos, 1997).

The time-to-collision of a vehicle-driver combination i at instant t with respect to a leading vehicle $i-1$ can be calculated with:

$$\mathrm{TTC}_i = \frac{X_{i-1}(t) - X_i(t) - l_i}{\dot{X}_i(t) - \dot{X}_{i-1}(t)} \qquad \forall \dot{X}_i(t) > \dot{X}_{i-1}(t) \tag{1}$$

where $\dot{X}$ denotes the speed, X the position, and l the vehicle length.

The time-to-collision notion is illustrated with two vehicle trajectories in Fig. 1. Depicted is a situation in which the lead vehicle $i-1$ brakes. After a reaction time τ, subject driver i starts a control action. According to expression (1), a time-to-collision value can only be calculated when a positive speed difference between the vehicles exists. Fig. 1 shows the TTC-value at instant t, the moment driver i starts braking.

For calculation of a TTC-value, the speed differential at instant t is assumed to remain constant during the hypothetical collision trajectories of the vehicles until instant t' (shown by the straight dashed lines). The higher a TTC-value, the more safe a situation is.

2.2. Critical time-to-collision value

Safety-critical approach situations are characterized by small TTC-values. In applying the developed, im-

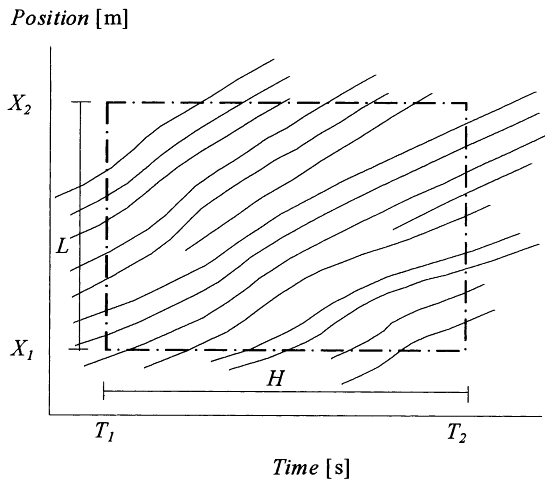

Fig. 2. Trajectories of vehicles observed over road length L during time period H.

proved safety indicators, a critical or *threshold value* should be chosen to distinguish relatively safe and critical encounters. Hirst and Graham (1997) report that a time-to-collision measure of 4 s could be used to discriminate between cases where drivers unintentionally find themselves in a dangerous situation from cases where drivers remain in control. The study further describes a laboratory experiment of the design of a Collision Warning System. The results show that a TTC warning criterion of 4 or 5 s results in too many false alarms. The study shows that a TTC-value of 3 s produced the least number of alarms although in some cases critical situations were observed. Hogema and Janssen (1996) studied the driver behavior at an approach of a queue for non-supported and supported drivers in a driving simulator experiment. They found a minimum TTC value of 3.5 s for the non-supported drivers, and 2.6 s for supported drivers. The 2.6 s value is regarded as a safety concern. VanDerHorst (1990) reports even lower critical TTC values, based on approaches at intersections.

2.3. Approaches for determining time-to-collision values

Basically, two approaches can be observed in literature to determine time-to-collision values for safety assessments (see previous paragraph). One approach focuses on time-to-collision values of vehicles passing a cross-section of a roadway. This method is mostly used in empirical traffic flow studies and in microscopic simulation studies. The other approach deals with subject drivers driving during a certain time period or following a specific route in real-life traffic conditions or under controlled conditions in a driving simulator. The driving performance of the subjects (including time-to-collision) is continually measured, so that afterwards minimum time-to-collision values can be determined.

Our proposal combines the two approaches which results into two new safety indicators (called TET and TIT). Instead of a single cross-section a specified road length is considered for safety analysis. With this approach, the occurrences of small time-to-collision values of all traffic participants, at any moment, can be taken into account.

3. A road-section based time-to-collision profile

In establishing the improved safety measures, let us consider a road section between X_1 and X_2. Example trajectories of vehicles driving at a road section are shown in Fig. 2. The considered road section length is denoted with L, the duration of the time period between T_1 and T_2 with H. It is now possible to determine the time-to-collision profile over time, $\mathrm{TTC}_i(t)$ for each of the vehicles i that use the road section, using expression (1). Such a time-to-collision value profile over time is shown in Fig. 3.

Shown in Fig. 3 (upper part) is the movement of a driver on a motorway lane. At instant $t = 0$ the driver approaches a slower driving vehicle, so the time-to-collision value decreases with time. At a certain moment t_1 the subject decides to make a lane change. The driver is confronted with a new leader at a smaller gap distance. The time-to-collision values are smaller and reach quite unsafe values. The driver adapts his speed to increase the gap distance and reduce the speed differential. Between t_2 and t_3 no positive TTC values are apparent. The lead vehicle is thus driving with a higher speed. However, at t_3 the subject approaches another lead vehicle. Drivers' car-following behavior exhibits this oscillatory behavior constantly, switching from a negative to a positive speed difference, in order to maintain a minimum desired gap distance. At t_6, the lead vehicle returns to the right lane, and a new lead vehicle is observed by the driver. The subject approaches this new leader without speed adaptations, so the TTC value decreases.

In Fig. 3 (upper part) a constant TTC threshold value (TTC*) is indicated (horizontal line), together with shaded areas if drivers' TTC values drop below this threshold value. The TTC threshold value is a time-to-collision value that can be applied to distinguish safe and safety-critical approach situations.

From the example, we observe that the time-to-collision values for a single driver may strongly vary over time. Based on such TTC-profiles, a number of more refined safety indicators will be derived in the sequel. An analysis approach is developed in which the individual time-to-collision profiles are used in the determination of a useful time-to-collision exposition distribution. A full description of the developed safety indicators TIT and TET is given in the following sections.

4. Definition of two TTC-based road traffic safety indicators

Two safety indicators are derived using the trajectories and time-to-collision profiles of all vehicles, observed over road section length L during time period H. Fig. 3 shows a trajectory profile of a driver (upper part) as well as the principle of the two safety indicators we developed (lower part). The definition of the two indicators is given below, after which calculation procedures are described based on measured TTC-frequencies.

4.1. The TET indicator

The first indicator we will specify is called TET, which stands for Time Exposed Time-to-collision. The duration of exposition to safety-critical time-to-collision values over specified time duration H is used here as safety indicator. It is a summation of all moments (over the considered time period) that a driver approaches a front vehicle with a TTC-value below the threshold value TTC*, the latter is considered to be the boundary between safe and safety-critical approaches. Thus, the lower the TET value, the more safe the situation (on average over period H). This safety measure does not take into account the variation in safety levels of different time-to-collision values below the threshold value.

Calculation of the TET indicator requires collection of the position and speed of all vehicles entering and leaving the specified road section between X_1 and X_2, over time period H, from which trajectories (Fig. 2) and time-to-collision profiles can be established. However, since data mostly is collected in discrete time, the TTC values will also be determined at discrete time moments (determined by time scan interval τ_{sc}). For calculation purposes it is assumed that the measured TTC-values at an instant t do not change during a small time step τ_{sc} (e.g. 0.1 s). For the considered time period H, there are $T = H/\tau_{sc}$ time instants t taken into account in the calculation ($t = 0 \ldots T$).

From Fig. 3, it can be concluded that the TET* indicator for a subject i can be expressed by:

$$\mathrm{TET}_i^* = \sum_{t=0}^{T} \delta_i(t) \cdot \tau_{sc}$$

$$\delta_i(t) = \begin{cases} 0 & \text{else} \\ 1 & \forall\, 0 \leq \mathrm{TTC}_i(t) \leq \mathrm{TTC}^* \end{cases} \tag{2}$$

in which δ is a switching variable. Its value is 1 in case a driver i at instant t experiences a TTC-value between 0 and the specified threshold value TTC*, otherwise, its value is 0.

The TET indicator is expressed in seconds. The superscript * should be interpreted as 'indicator value calculated with respect to the threshold value'. It can easily be understood that for a population of N drivers ($i = 1 \ldots N$), the total TET* is equal to:

$$\mathrm{TET}^* = \sum_{i=1}^{N} \mathrm{TET}_i^* \tag{3}$$

The TET indicator can also be calculated separately per user class, e.g. trucks and passenger cars, or equipped and non-equipped vehicles, by adding an extra index and summation per user class.

4.2. The TIT indicator

One disadvantage of the TET indicator is that the TTC-value if it is lower than the threshold does not affect the TET indicator value. However, according to the theory, it may be expected that an extremely small

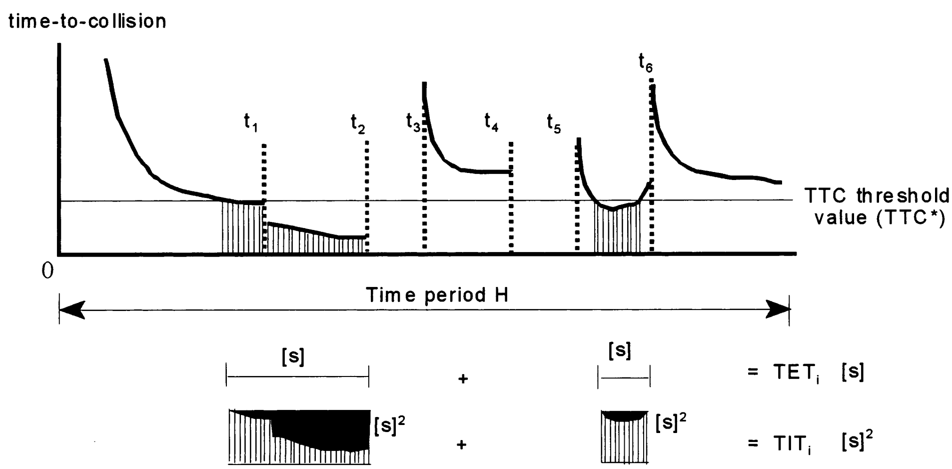

Fig. 3. Example time-to-collision profile of a driver-vehicle-combination i in motorway traffic (lightly shaded areas represent safety-critical approach conditions).

TTC-value (e.g. smaller than 0.5 s) represents an approach situation with a relatively high probability of a collision compared to higher TTC-values (e.g. 2 or 3 s). For example, the approach situation between t_1 and t_2 in Fig. 3 can be considered to be more dangerous than the approach between t_5 and t_6. To take the impact of the TTC-value into account in the safety assessment, the TIT indicator has been developed.

The TIT (= Time Integrated Time-to-collision) indicator uses the integral of the time-to-collision profile of drivers to express the level of safety (in s^2). In continuous time:

$$\mathrm{TIT}^* = \sum_{i=1}^{N} \int_0^T [\mathrm{TTC}^* - \mathrm{TTC}_i(t)]\mathrm{d}t$$

$$\forall\, 0 \le \mathrm{TTC}_i(t) \le \mathrm{TTC}^* \qquad (4)$$

The lightly shaded areas in Fig. 3 represent situations in which the driver approaches the front vehicle with TTC-values below TTC*. Since low TTC-values represent more dangerous situations, it holds that the smaller the shaded area, the higher the risks of collisions. To be consistent with the TET-indicator, the shaded area should be subtracted from the area below the threshold value, resulting in a time integral with an interpretable meaning. This area is shown in Fig. 3 by a dark surface. A high TIT value means a large exposition time to duration-weighted unsafe TTC-values, which is negative for road safety. The individual TIT for subject i in discrete time can be calculated with:

$$\mathrm{TIT}_i^* = \sum_{t=0}^{T} [\mathrm{TTC}^* - \mathrm{TTC}_i(t)] \cdot \tau_{\mathrm{sc}}$$

$$\forall\, 0 \le \mathrm{TTC}_i(t) \le \mathrm{TTC}^* \qquad (5)$$

Summation over all vehicles ($i = 1\dots N$) present in the investigation during time period H, results in the following discrete-time aggregate TIT definition (expressed in s^2):

$$\mathrm{TIT}^* = \sum_{i=1}^{N} \mathrm{TIT}_i^* \qquad (6)$$

The aggregate indicator values (3) and (6) hold for the population of all observed vehicles N, and depend on the considered time period H. The population size N depends on the beginning and ending of the time horizon, see Fig. 2. One should consider the number of vehicles already present on the road section at moment T_1, as well as the number of vehicles still present on the road section at the end of the considered period, at T_2.

From the aggregate TET and TIT indicators, other indicators can be derived, such as corresponding average values per vehicle, as well as the probability of safety-critical situations per time unit (see Section 5). In order to calculate the various indicators in practical circumstances it is advantageous to use frequency distributions of measured TTC-values.

5. Calculation procedures of TET and TIT indicators

For the construction of a TTC-frequency distribution, which is useful for visual inspection and analysis of the impact of the threshold value on the indicator value, we distinguish TTC-classes denoted with index k. Assuming an equal size of the classes set at a and TTC-values ranging from 0 to MAX seconds, the boundaries of the TTC classes in the frequency distribution then are defined by $\mathrm{TTC}^k = (k-1) \cdot a$, where $k = 1\dots\ \mathrm{MAX}/a$.

The summed exposition time with TTC-values within a particular TTC-class k over period H is calculated by:

$$\mathrm{TET}^k = \sum_{i=1}^{N} \sum_{0}^{T} \delta_i^k(t) \cdot \tau_{\mathrm{sc}}$$

$$\delta_i^k(t) = \begin{cases} 0 & \text{else} \\ 1 & \forall\, \mathrm{TTC}^k \le \mathrm{TTC}_i(t) < \mathrm{TTC}^{k+1} \end{cases} \qquad (7)$$

From Eq. (7) it follows that the TET* indicator (3) can be determined by:

$$\mathrm{TET}^* = \sum_{k=1}^{k*} \mathrm{TET}^k \qquad \forall\, k = 1\dots k^* \qquad (8)$$

where k^* represents the index of the class corresponding with a TTC-value equal to the threshold value TTC*. The class index k^* can be calculated from $k^* = \mathrm{TTC}^*/a$.

Given the TET-values per class k, the aggregate TIT indicator (6) can easily be derived. Firstly, it should be obvious that holds:

$$\delta_i(t) = \sum_{k=1}^{k*} \delta_i^k(t) \qquad (9)$$

since from Eq. (2) it follows that a subject i with a time-to-collision value below TTC* at instant t corresponds to a switching variable value of $\delta_i(t) = 1$. The time-to-collision value is also element of the TTC-frequency distribution; the time instant will be assigned to one of its classes k. Summation of $\delta_i^k(t)$ over index k will result in the same value as found for the switching variable $\delta_i(t)$.

The aggregate TIT* indicator (6) can be derived from the TTC-frequency distribution. Graphically, it can be observed that for TIT* holds:

$$\mathrm{TIT}^* = N \cdot T \cdot \mathrm{TCC}^* \cdot \tau_{\mathrm{sc}} - \sum_{i=1}^{N} \sum_{t=0}^{T} \mathrm{TTC}_i(t) \cdot \tau_{\mathrm{sc}}$$

$$\forall\, 0 \le \mathrm{TTC}_i(t) \le \mathrm{TTC}^* \qquad (10)$$

where the first part of the equation represents the area below TTC* for time instants with a TTC-value meeting the condition $0 \le \mathrm{TTC}_i(t) \le \mathrm{TTC}^*$, and the second part representing the area below the curve (see Fig. 3) for time instants meeting the same condition. This subtraction of areas results in the TIT* indicator; it is equal to the area below the threshold value and above the TTC-profile, again for time instants meeting the

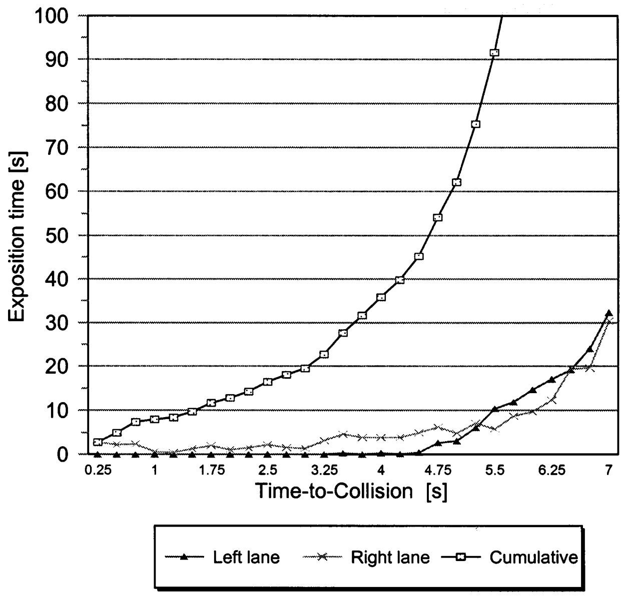

Fig. 4. Exposition time versus time-to-collision (two-lane motorway without AICC-equipped vehicles).

previous mentioned condition. Eq. (10) can be formulated also using the TET indicator by substituting $\mathrm{TTC}_i(t) \cdot \tau_{sc}$ according to the following relationships:

$$\mathrm{TCC}_i(t) \cdot \tau_{sc} = \sum_k \mathrm{TTC}_i^k \cdot \tau_{sc}$$

$$= \sum_k \delta_i^k(t) \cdot \mathrm{TTC}^k \cdot \tau_{sc}$$

$$= \sum_k \mathrm{TET}_i^k \cdot (k-1) \cdot a \tag{11}$$

The TIT* calculation with the aid of the TTC-frequency distribution is less exact than using the vehicle trajectory approach (Sections 4–6) since the exposition time of unsafe TTC-values are aggregated into classes of TTC-values defined by class width parameter a, thus losing information of the precise TTC-value observed. Nonetheless, the method simplifies the data collection effort while the estimated indicator value is sufficiently accurate for assessing safety impacts.

5.1. Related specific safety indicators

We developed two related time-to-collision safety indicators which can advantageously be applied in the analysis of traffic safety. For comparative purposes it is desirable to standardize the indicator values relative to the sample size and duration of the observations.

We may standardize the aggregate TET and TIT indicator values into an average value per vehicle, denoted with $\overline{\mathrm{TET}}*$ and $\overline{\mathrm{TIT}}*$, respectively:

$$\overline{\mathrm{TET}}* = \frac{\mathrm{TET}*}{N} \qquad \text{(s/vehicle)} \tag{12}$$

It is the expected average duration that a vehicle encounters an unsafe situation.

$$\overline{\mathrm{TIT}}* = \frac{\mathrm{TIT}*}{N} \qquad (\mathrm{s}^2/\text{vehicle}) \tag{13}$$

The average TIT* per vehicle expresses the expected duration-weighted exposition to unsafe TTC-values (over time period H).

These average indicators still include the time period over which the indicator value has been determined. To overcome this dependency, an indicator $P*$ can be established, expressing the probability that a vehicle encounters a safety-critical approach situation, which is defined as a moment with a TTC-value between 0 and TTC* second. The TET* probability per vehicle is therefore:

$$\mathrm{TET}\ P* = 100 \cdot \frac{\overline{\mathrm{TET}}*}{H} \qquad (\%) \tag{14}$$

The probability indicator can be interpreted as the percentage of time that a random driver on average drives with TTC-values below the threshold TTC*. This indicator is calculated by dividing the average indicator value of Eq. (7) by the maximum attainable time period (thus H).

Analogously, the TIT* probability indicator can be calculated with:

$$\mathrm{TIT}\ P* = 100 \cdot \frac{\overline{\mathrm{TIT}}*}{\mathrm{TTC}* \cdot H} \qquad (\%) \tag{15}$$

in which the $\overline{\mathrm{TIT}}*$ is divided by the theoretically maximum attainable *TIT* indicator value per vehicle (thus $H \cdot \mathrm{TTC}*$).

The following section presents an example of the frequency distribution of the TET indicator, and concentrates on the impact of the chosen threshold value on the TET indicator values.

6. Illustration of derived TET indicator: a TTC-frequency distribution

Dividing the time-to-collision range in classes with $a = 0.25$ s, a TTC-frequency distribution of the aggregate indicator value TET per class k can be calculated according to Eq. (7).

Fig. 4 shows the calculated TTC-frequency distribution for simulated traffic on a 5 km long two-lane motorway stretch with an on-ramp bottleneck (see Minderhoud, 1999; Minderhoud and Bovy, 1999a,b). Only the traffic on the two mainline lanes is considered in the analysis. On the x-axis the TTC range between 0 and 7 s is depicted, on the y-axis the exposition time per TTC class is shown. For a class k, the exposition time (TET indicator) is calculated according to Eq. (7).

Also shown in Fig. 4 is the cumulative exposition to unsafe TTC-values. For the cumulative distribution, the values on the y-axis correspond with the aggregate TET* indicator value, assuming a threshold TTC-value on the x-axis.

The three-second threshold is considered an adequate level for discriminating dangerous approach situations from acceptable situations, as has been observed by Hirst and Graham (1997). In our example, the safety indicator TET* with a threshold TTC-value TTC* of 3 results in a value of approximately 19.5 s. Nevertheless, other TTC-threshold values can be applied.

The calculated aggregate TET indicator value of 19.5 s implies that during the 2.5-h simulation run only about 19 s of potential dangerous situations have occurred with TTC-values below 3 s. Assuming a total of 10 000 vehicles generated in the simulation, the average exposition time of safety-critical TTC-values is 19.5×10^{-4} s per vehicle.

The probability (denoted with TETP*) that a driver is confronted with an unsafe situation is relatively small. In our example, the simulation time is 9000 s and about 10 000 vehicles traversed the observed motorway segment. The percentage of time that a random vehicle in the given simulation experienced unsafe conditions is then 2.2×10^{-7} on average. This probability is quite small. Even if a driver experiences a situation with a small time-to-collision value, this will mostly not result in a rear-end collision.

The TET indicator value is especially useful in a comparative analysis of scenarios. The TIT indicator, while being more adequate, is more complex to determine and more difficult to interpret its meaning. In addition, the threshold value adopted in studies differs largely, affecting the safety assessment substantially. Although the TIT measure is theoretically a preferable indicator, the TET indicator is preferred for use in comparative studies in which simulation tools are applied to generate trajectories. Due to the simplifications and uncertainties in modeled driver behavior, the additional benefits of the more complex TIT approach seem small.

7. Application to intelligent driver support systems

We will illustrate the use of the developed safety indicators by showing the impact of different vehicle fleet compositions on the TET* safety indicator values. Let us assume a future situation in which vehicles are equipped with intelligent driver support systems. The so-called AICC is able to actively support the driver in distance keeping and speed adaptation, thus enhancing driver comfort while it interacts on driver performance. One of the expected safety benefits of AICC use is that the system is able to perform the longitudinal driving task without temporarily decreasing the attention level, without moments of arousal, or other temporarily inattentive behavior. A safety decrease is also possible, since the gap distance can be shorter, whereas driver intervention is required in some cases. It is important to understand the decisive role of the applied simulation tool in the analysis of safety impacts. The applied microscopic simulation tool consists of a state-of-the-art model of individual driving behavior on multilane motorways (including car following, speed choice, lane changing, etc.), extensively calibrated and validated with empirical data, where even the driver behavior with respect to handling of the AICC-equipment in his car is modeled in detail (see for details Minderhoud, 1999; Minderhoud and Bovy, 1999a,b). The model represents AICC behavior quite well, but does not model driver errors and assumes constantly alert drivers. This affects the outcome of the safety indicators, probably overestimating the safety of non-supported driving.

It can be hypothesized that traffic safety can be increased with some AICC designs that fully assist the driver, even if it is observed that the frequency of small TTC values increases compared to the reference case without AICC. The resulting indicator values of the various scenarios can not be compared easily due to the different driving characteristics in case of a fully controlled and manually controlled vehicle. We expect that lower TTC-threshold values may be applied for these advanced driver assistance systems (for e.g. a 2 s TTC-threshold) because of their more adequate response behavior in case of dangerous situations.

Table 1
Estimated TET indicator values for a sample of AICC scenario's as function of threshold value

	TTC* = 1 s		TTC* = 2 s		TTC* = 3 s	
	Left lane	Right lane	Left lane	Right lane	Left lane	Right lane
Reference	0	8.0	0	12.8	0	19.5
50% AICC-partial	0	3.9	0.3	8.4	13.1	18
100% AICC-partial	0	5.2	4.4	11.5	634	93.6
50% AICC-complete	0	6.5	0	19.3	0	44.2
100% AICC-complete	0	10.8	3.4	26.2	4.7	69.9

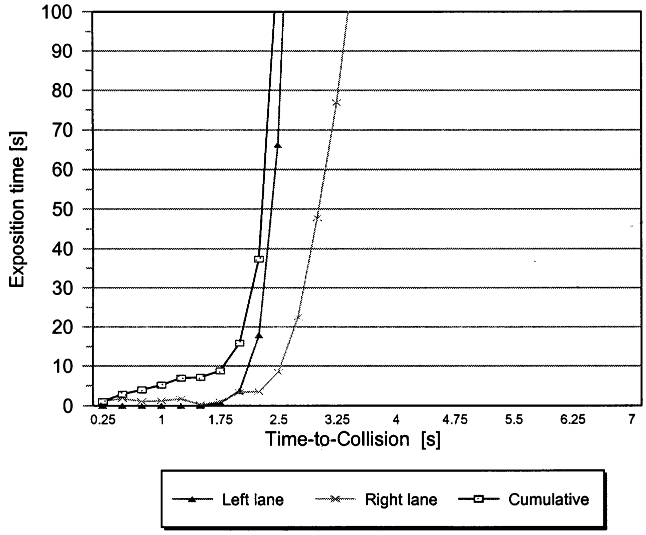

Fig. 5. Exposition time versus time-to-collision (two-lane motorway with 100% AICC-partial equipped vehicles).

Table 1 gives an overview of the TET* safety indicator values found in the simulation experiments of a 5 km long two-lane motorway stretch with on-ramp bottleneck (see Minderhoud, 1999). A high TET* value means a high exposition duration to safety-critical approach situations. A value of 0 implies that there is no safety concern (with respect to the selected threshold value for distinguishing between safe and dangerous approaches). A comparison is made of the safety indicator values estimated for two AICC-designs (partial and complete, respectively) at two penetration levels (50 and 100%, respectively). In addition, three threshold values are considered: 1, 2 and 3 s. The AICC systems are characterized by the following:

1. AICC-partial: driver must intervene if the speed drops below 30 km/h or needed deceleration arrives at -3 m/s^2. The system has a target headway setting of 0.8 s.
2. AICC-complete: driver is fully supported. The system has a target headway of 0.8 s.

From Table 1 it can be seen that the AICC-partial at 100% penetration has extreme large indicator values if applying the 3 s threshold value, which is a safety concern. The high TET* value is caused by the needed driver intervention as drivers approach the bottleneck, while speeds below 30 km/h are not supported. After driver intervention, drivers expand their gap distance to their normal preferred distance, which is larger than the target 0.8 s headway the AICC-system maintained. It is apparent that this leads to shock waves (especially on the left lane) and safety-critical time-to-collision values, nonetheless, no rear-end collisions were observed in the simulation.

The table shows that the safety-critical time-to-collisions are mainly found on the right lane, since merging vehicles from the on-ramp enter the mainline on the right lane. Fig. 5 shows the frequency distribution of the AICC-partial at 100% penetration, from which the impact of the selection of a threshold value can be observed graphically. It is observed that large and safe TTC-values (e.g. 8 s) are more frequently encountered than safe-critical small values (e.g. 2 s).

From Fig. 5, the impact of the threshold value on the exposition time is obvious. The smaller the TTC threshold value, the smaller the overall exposition time TET* (indicated by the cumulative distribution).

It is speculated that AICC-systems will improve the driving performance and reduce the safety risks due to quick response behavior, less errors, etc. so we may select a smaller threshold value that expresses the attainable safety levels realistically. The adequate threshold value depends on the design characteristics of the AICC-system and how the traffic safety level eventually will be influenced by these features. However, determining such a system-dependent threshold value is difficult since empirical data is not yet available. Therefore another simplified approach is followed. It is decided to adapt the threshold value belonging to certain system types to the safety level found in the do-nothing case. For the AICC-partial it appears that the 2 s boundary results in an indicator value that approximates the reference. The 1 s threshold fits better for the AICC-complete at 100% penetration. The AICC-complete is more advanced than the AICC-partial, so it appears logical that safety analysis of the AICC-complete should adopt a lower threshold value.

In the example, the safety indicator has been determined per lane, which resulted in the conclusion that the right lane contributes largely to the safety-critical situations. The analysis could be easily extended by introducing user class specific indicator values, giving the possibility to compare the performance between user classes (e.g. equipped and non-equipped vehicles). This could give essential information about the safety-critical behavior of particular groups of users.

8. Summary and implications

In this article we described two new safety indicators based on extensions of the time-to-collision safety measure. In contrast to the classical TTC-indicator, these extensions can take the full course of vehicles over space and time into account. The extended indicators therefor can give a more complete and comprehensive picture of the safety level on a particular stretch of road during a particular period of time. The developed TET indicator expresses the exposition time to safety-critical approach situations, whereas the developed TIT indicator additionally takes into account the encountered TTC-values during these safety-critical approaches. The safety assessment approach can be applied for a single driver, a specified user class, or all vehicles that pass the road segment during a time period, and can distinguish impacts per lane. Advantage of the TET and TIT safety measures above the conventional time-to-collision measure is the inclusion of time-dependent time-to-collision values of all subjects that use a road section during a time period. This means that the occurrence of small TTC-values, which can hardly be measured at a single cross-section of the roadway, will be included as well.

These new measures appear to be fruitful safety measures that can be used most beneficially in microscopic simulation studies focusing on safety impacts such as of intelligent driver support systems. However, the methodology presented can also be applied to empirical data, if available. A threshold value should be specified in accordance with the design characteristics of the AICC-devices in order to make valid comparisons of the safety impacts.

Acknowledgements

The authors are grateful to two anonymous referees whose comments were very helpful in improving the text.

References

Fancher, P., Koziol, J., Baker, M., 1997. Preliminary results from the Intelligent Cruise Control field operational test in Southeastern Michigan. Proceedings of the 4th Annual World Congress on Intelligent Transport Systems, Berlin.

Hirst, S., Graham, R., 1997. The format and presentation of collision warnings. In: Noy, N.I. (Ed.), Ergonomics and safety of Intelligent Driver Interfaces.

Hogema, J.H., Janssen, W.H., 1996. Effects of intelligent cruise control on driving behavior. TNO Human Factors, Soesterberg, The Netherlands, Report TM-1996-C-12.

Hyden, C., 1996. Traffic conflicts technique: state of the art. In: Topp, H.H. (Ed.), Traffic safety work with video processing. University Kaiserslautern, Transportation Department, 1996, Green Series No. 37, pp. 3–14.

Minderhoud, M.M., 1999. Supported driving: impacts on motorway traffic flow. Delft University Press, Delft, The Netherlands, 1999, TRAIL Thesis Series T99/4.

Minderhoud, M.M., Bovy, P.H.L., 1999. Impact of AICC design on motorway capacity. In Transportation Research Record no. 1679, 1999a, pp. 1–9.

Minderhoud, M.M., Bovy, P.H.L., 1999b. Development of a microscopic simulation model for AICC. Proceedings of the 6th Annual World Congress on Intelligent Transport Systems, Toronto.

Topp, H.H. (Ed.), 1998. ViVa traffic: video verkehrs analyse in der praxis (in German). University Kaiserslautern, Transportation Department, 1998, Green series No.43.

VanArem, B., DeVos, A.P., 1997. The effect of a special lane for intelligent vehicles on traffic flows. TNO-INRO Report 1997-02a. Delft, The Netherlands.

VanDerHorst, A.R.A., 1990. A time-based analysis of road user behavior in normal and critical encounters. Dissertation Delft University of Technology, The Netherlands.