TIME-TO-COLLISION AND COLLISION AVOIDANCE SYSTEMS

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ABSTRACT

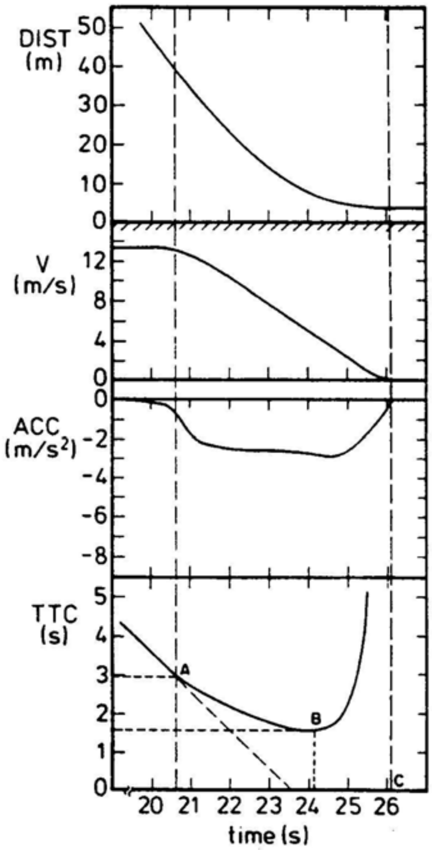
In research on Traffic Conflicts Techniques, Time-To-Collision (TTC) has proven to be an effective measure for rating the severity of traffic conflicts and for discriminating critical from normal behaviour. The results of several studies point to the direct use of TTC as a cue for decision-making in traffic. The current development of driver support systems based on the application of modern technologies makes it necessary to have detailed knowledge on how drivers operate, and at what level and when a system should warn the driver or take action. An important issue in developing Collision Avoidance Systems (CAS) is to define a proper warning strategy, that warns the driver only when the driver is really at danger and immediate action is required. Misses should be avoided, but too many false alarms may easily cause the system to become a nuisance to the driver.

The present paper deals with the use of the TTC measure to define an adequate criterion for activating a driver support system such as CAS in order to reduce the number of rear-end collisions on a motorway. Reduced visibility conditions (e.g. due to fog) frequently cause multi-vehicle crashes with very severe consequences. The results of a field experiment where subjects approaching a stationary object were instructed to start braking at the latest moment, reveal that both the decision to start braking and the control of braking may well be based on TTC information available from the optic flow field. First tests with Collision Avoidance Systems (CAS) indicate that warning strategies based on a TTC-criterion are preferred by the drivers and seem to be most in line with what drivers expect to get from a CAS. These tests only refer to a fixed 4 s TTC-criterion. Recently, some studies on driver behaviour in fog enable a more precise definition of CAS-critical situations and relevant criterion values for TTC. Based on the analysis of driver behaviour in adverse visibility conditions, it is concluded that it is worthwhile to investigate a TTC criterion in the range of 4.5 to 5 s for activating a CAS. Especially in the visibility range between 40 and 120 m free-driving speeds are too high, and therefore, special attention should be given to this distance range when developing a CAS.

1 INTRODUCTION

Systematic observations of road user behaviour in various traffic situations combined with knowledge of human information processing capabilities and limitations, offer good perspectives in understanding the causes of safety problems. In particular, the study of conflict behaviour is a natural candidate for that purpose; the processes that result in near-accidents or traffic conflicts have much in common with the processes preceding actual collisions (Hydén, 1987), except for that the final outcome is different. The frequency of occurrence of near-accidents is relatively high, and they offer a rich information source on causal relationships. The process preceding conflicts can be systematically observed, which is essential for analysing, diagnosing, and solving traffic safety problems. The analysis of road user behaviour in critical encounters may not only offer a better understanding of the processes that ultimately result in accidents, but, perhaps even more important and efficient in the long run, also provide us with knowledge on road users' abilities of turning a critical situation into a controllable one. An important issue is how to distinguish critical from normal behaviour. The results of several studies point to the direct use of time-related measures as a cue for decision-making in traffic. In research on Traffic Conflicts Techniques, Time-To-Collision (TTC) has proven to be an effective measure for rating the severity of conflicts. Hayward (1972) defined TTC as: "The time required for two vehicles to collide if they continue at their present speed and on the same path". TTC at the onset of braking, TTC_{br}, represents the available manoeuvring space at the moment the evasive action starts. The minimum TTC as reached during the approach of two vehicles on a collision course (TTC_{min}) is taken as an indicator for the severity of an encounter. In principle, the lower the TTC_{min}, the higher the risk of a collision has been. To illustrate TTC, Fig. 1 shows what happens when a car approaches a stationary object. TTC_{min} indicates how imminent an actual collision has been. Details of the calculation of TTC can be found in Van der Horst (1990).

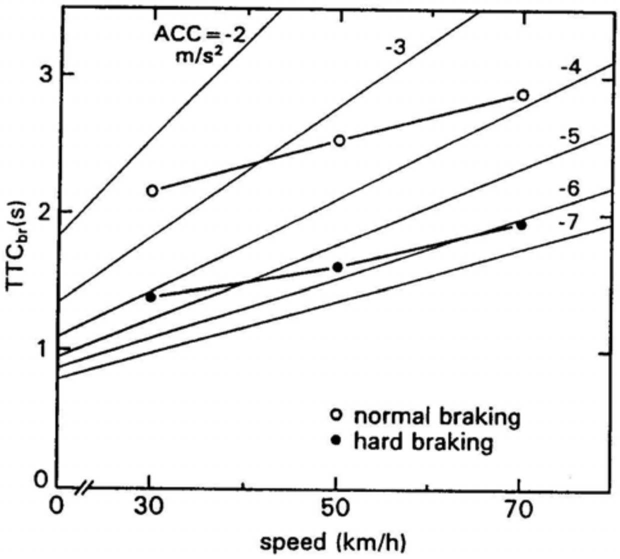
Fig. 1 Time histories of braking by a car approaching a stationary object; DIST = distance to object, V = velocity, ACC = acceleration, and TTC = Time-To-Collision based on constancy of speed and heading angle. Point A indicates TTC_{br} and point B TTC_{min}.



In general, only encounters with a minimum TTC less than 1.5 s are considered critical and trained observers appear to operate rather consistently in applying this threshold value (Grayson (ed.), 1984; van der Horst, 1984; Kraay & van der Horst, 1985; Hydén, 1987; van der Horst, 1990). When analyzing all encounters occurring at an intersection, encounters, in general, hardly display a TTC_{min} less than 1.5 s.

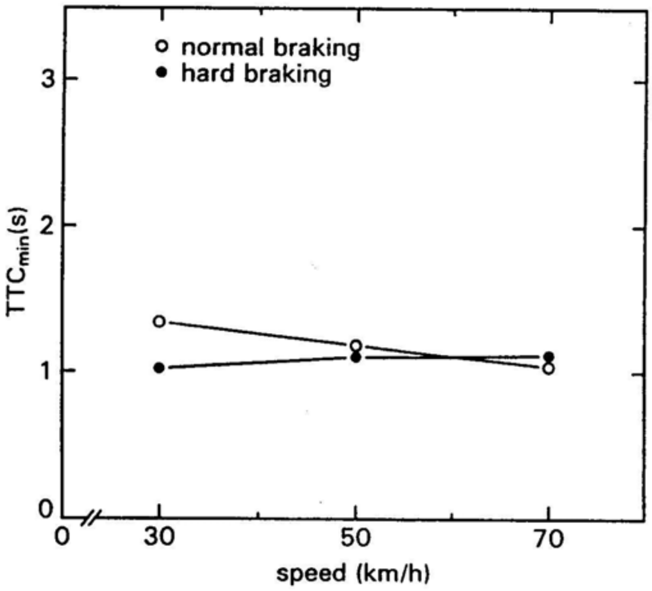
In a study on drivers' strategies of braking, it was found that both the decision to start braking and the control of the braking process itself may well be based on TTC information as directly available from the optic flow field (van der Horst, 1991). In this field experiment, subjects approaching a stationary object (simulated rear end of a small passenger car) with a given speed, were instructed to start braking at the latest moment they thought they could stop in front of the object. Fig. 2 reveals that TTC_{br} increases with speed, but less than could be expected on the basis of a constant deceleration model as represented by the fan of lines. The effect of braking instruction (start normal braking at the latest moment you think you can stop safely vs. hard braking at the latest moment you think you are able to stop in front of the object) indicates that subjects are able to apply the given instruction well, independent of approach speed.

Fig. 2 TTC_{br} as a function of approach speed and braking instruction (van der Horst, 1990).



The minimum TTC as reached during the approach appears to be independent of approach speed and normal or hard braking instruction and reaches a value of about 1.1 s, on an average (Fig. 3).

Fig. 3 TTC_{min} as a function of approach speed and braking instruction (van der Horst, 1990).



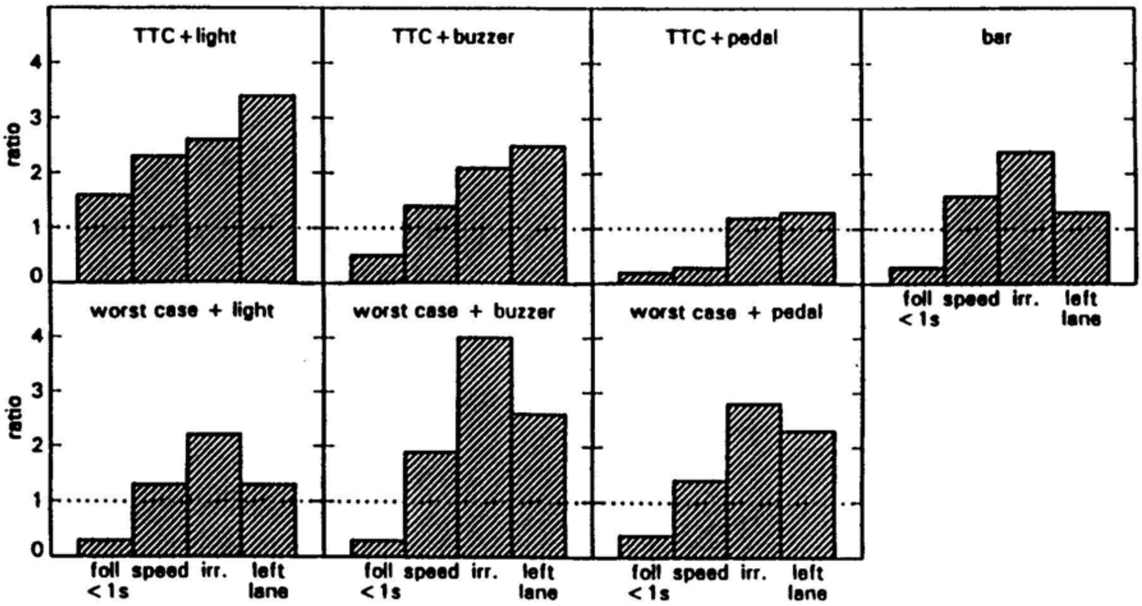
Since in this study the subjects were instructed to start braking at the latest moment they thought they could stop just in front of the object, the TTC_{br} values from Fig. 2 have to be regarded as absolutely minimal for activating a Collision Avoidance System. Together with an 1.5 s reaction time (with the time needed for moving the foot from the gas to the brake pedal included), an average TTC_{br} of 2.5 s would result in a TTC-criterion of 4 s.

In the next chapter the first evaluation tests of applying this criterion value for activing a CAS will be briefly discussed. Since adverse visibility conditions such as fog enable a more precise description of critical approach situations and provide information on what criterion value for TTC should be used, some recent studies on driver behaviour in adverse visibility conditions have been critically reviewed. This paper concludes with a discussion on the consequences for defining an efficient CAS.

2 TTC IN COLLISION AVOIDANCE SYSTEMS

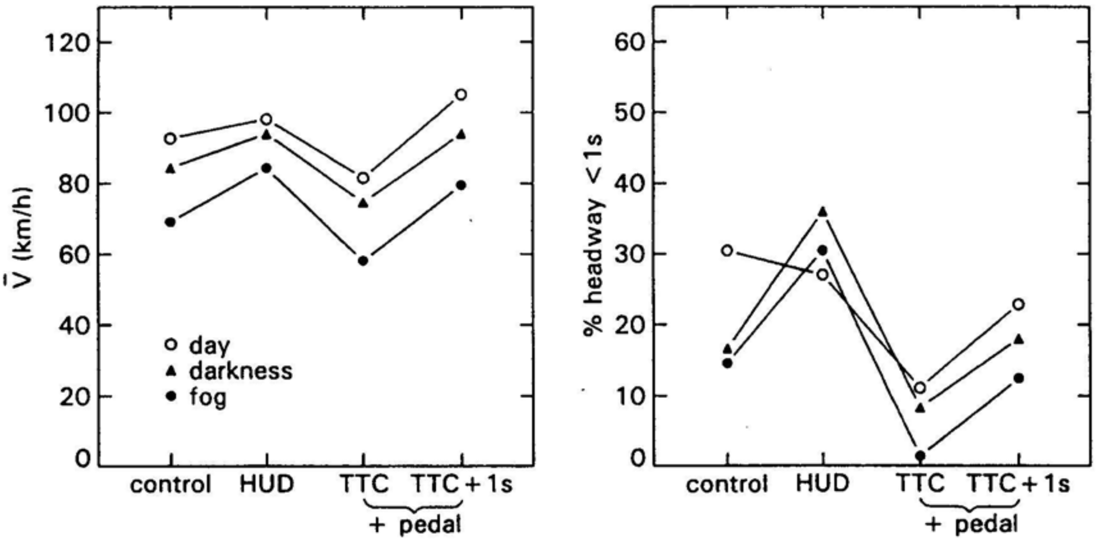
Within the DRIVE project GIDS (Generic Intelligent Driver Support) Janssen and Nilsson (1990) compared seven Collision Avoidance Systems (CAS) in an experiment in the TNO driving simulator. They combined two different CAS criteria with three possible system warning actions, viz. via a buzzer, a red warning light on the dashboard, or an active gas pedal. The two CAS criteria consisted of a 'worst-case'-criterion (at each moment the lead vehicle can brake with maximum deceleration) or a TTC-criterion of 4 s. In case the following vehicle drives at an higher speed than the lead vehicle, TTC is defined as the distance to the lead vehicle divided by the relative speed. The seventh CAS consisted of a continuous displaying of the momentaneous braking distance by a horizontal red line on the windscreen via a HUD (Head Up Display). Each subject made two runs, one without and one with a CAS, on an undivided rural road with lead vehicles driving at varying speeds. In Fig. 4 the effects of the different CASs on four performance measures are presented as a ratio relative to a control group. Ratios > 1 have to be regarded as a negative safety effect. Most systems give a reduction of the proportion of short headways, but this frequently resulted in contra-productive effects on the other behavioural measures. The combination of the 4 s TTC-criterion and the active gas pedal does not produce contra-productive effects and has been selected for the CAS in the prototype GIDS system.

Fig. 4 Behavioural effects of 7 Collision Avoidance Systems (Janssen & Nilsson, 1990) on a) the percentage of headways < 1 s (foll. < 1s); b) average speed (speed); c) speed irregularities (irr.); d) the percentage of time the vehicle is in the opposite lane (left lane).



In a study within the DRIVE-II project ARIADNE (Application of a Real-time Intelligent Aid for Driving and Navigation Enhancement), V2004, Janssen and Thomas (1993) compared three CASs in the TNO driving simulator for car-following situations under adverse visibility conditions (normal daytime, darkness and fog). These systems included the HUD as tested by Janssen and Nilsson (1990), the selected 4 s TTC-criterion with an active gas pedal, and a combined 4 s TTC and an 1 s headway criterion (whichever came first) with an active gas pedal. The results reveal that, again, the combination of a 4 s TTC-criterion and an active gas pedal reduces the proportion of small headways most without an increase in speed (Fig. 5), both in daytime and under reduced visibility.

Fig. 5 Effects of three Collision Avoidance Systems on mean speed (left panel) and on the proportion of headways < 1 s (right panel) (Janssen & Thomas, 1993).



In conclusion, the CAS with a 4 s TTC-criterion and an active gas pedal that produces a counter-force as a direct warning to the driver gives the best results and seems most in line with what drivers expect to get from a CAS. So far, only one TTC criterion value for activating the CAS has been applied. The question arises whether the 4 s TTC-criterion is to be regarded as the optimal setting or whether other values may apply too. To explore these questions in more detail, in the following chapter the results from two recent studies on driving behaviour in adverse visibility conditions will be critically reviewed, as these conditions especially provide situations that are relevant for applying a CAS in preventing rear-end collisions on a motorway.

3 DRIVER BEHAVIOUR IN GOOD AND POOR VISIBILITY CONDITIONS

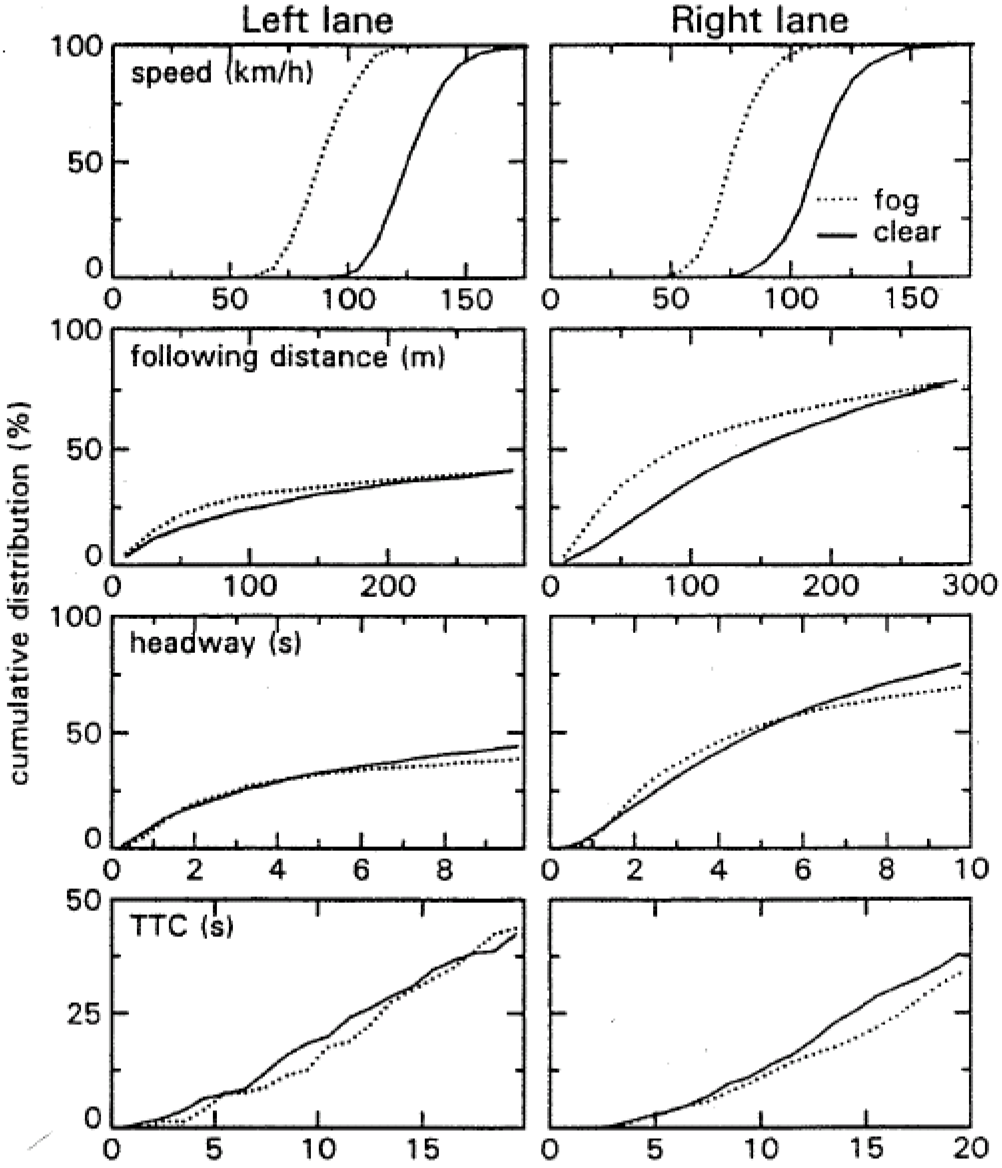
Within the DRIVE-II project ROSES (Road Safety Enhancement System) V2045, two studies on driver behaviour in adverse visibility conditions have been conducted. Section 3.1 briefly reports on an analysis of inductive loop detector data combined with continuous visibility measurements in real traffic, whereas Section 3.2 summarizes a simulator experiment on driver behaviour in fog in both daytime and nighttime conditions (van der Horst et al., 1993; Hogema & van der Horst, 1993a; 1993b).

3.1 Inductive loop data

For over a year inductive loop detector data have been collected on the A59 two-lane motorway near the city of Breda, The Netherlands, together with visibility measurements from a nearby scatter type sensor on a continuous one minute basis. For each individual vehicle, speed, vehicle length, following distance, headway, and Time-To-Collision (TTC) were available. The latter is defined as the following distance divided by the speed difference between following and lead vehicle (only if speed of the following vehicle is larger than the lead vehicle 's speed).

As an example, the cumulative distributions of the driver behaviour variables in a period of heavy fog are contrasted with a clear view period with otherwise similar characteristics (day of the week, time of day, traffic volume, etc.), see Fig. 6. During this fog period the visibility was less than 50 m, according to the standard definition for the Meterological Visual Range (MVR), e.g. White & Jeffery (1980).

Fig. 6 Cumulative distributions of speed, net following distance, headway, and TTC in fog (Meteorological Visual Range 50 - 60 m) and clear view conditions for the right and left lane on the A59 motorway.

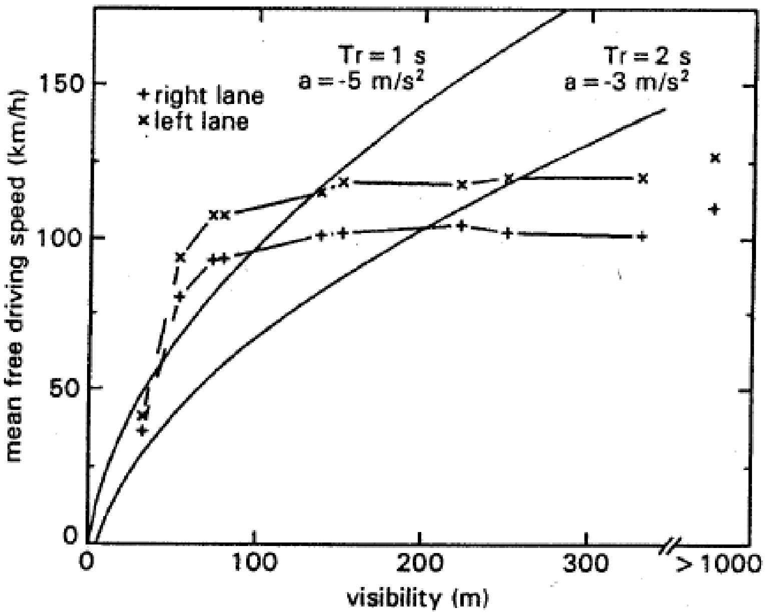


Various other fog periods give similar results, viz.:

- Speeds are much lower in fog than in clear visibility, but speeds in the left lane remain higher than in the right lane.
- Following distances decrease in fog, especially in the right lane.
- In general, fog has only minor effects on headway distributions.
- TTC values tend to increase in fog. TTCs less than 5 s are rarely observed.

Fig. 7 shows the mean free driving speed as a function of visibility (free driving defined as having a headway > 5 s). Added are two lines that indicate the (maximum) initial speed possible as a function of the required stopping distance, one for a rather extreme case of a short reaction time (1 s) and hard braking (acceleration - 5 m/s^2 with no safety margin left), whereas the right line corresponds to a more moderate reaction time and deceleration level.

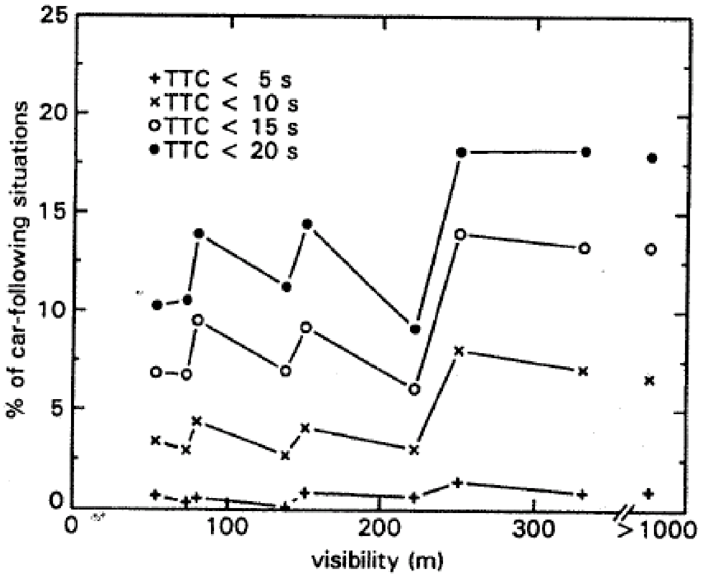
Fig. 7 Mean free driving speed as a function of visibility on the A59 motorway (general speed limit of 120 km/h), and initial speed possible as a function of the required stopping distance.



Even in the extreme case, the speeds of the free driving vehicles are too high to avoid a collision when the driver is suddenly confronted with a stationary object (e.g. a stopped vehicle) in a visibility range between 40 and 120 m. Hogema and Van der Horst (1993a) computed other scenarios as well and concluded that drivers at mean speed may be able to slow down in time for lead vehicles that drive with a speed of at least 38 km/h and 53 km/h in the right and left lane, respectively.

In fog conditions, the percentage of following situations with a given TTC value decreases rather suddenly at a visual range of about 230 m (see Fig. 8), i.e. TTC values increase. When visibility decreases further, no additional effect is found. TTCs < 5 s are rarely observed, and consequently, no significant effect could be established. However, the few observations available seem to indicate a lower percentage in that range as well.

Fig. 8 Percentages of all following vehicles with TTC below the given values as a function of visibility.



3.2 Simulator study

The results of the inductive loop data analysis only refer to the behaviour at one cross-section of the motorway. Although this approach has the advantage that a huge amount of data on road user behaviour in real traffic is available, the dynamics of car-following behaviour can not be studied this way. To study car-following behaviour of drivers over time and to have full control over the experimental conditions, a driving-simulator study has been conducted on car-following behaviour in both good and adverse visibility conditions (day/night, fog).

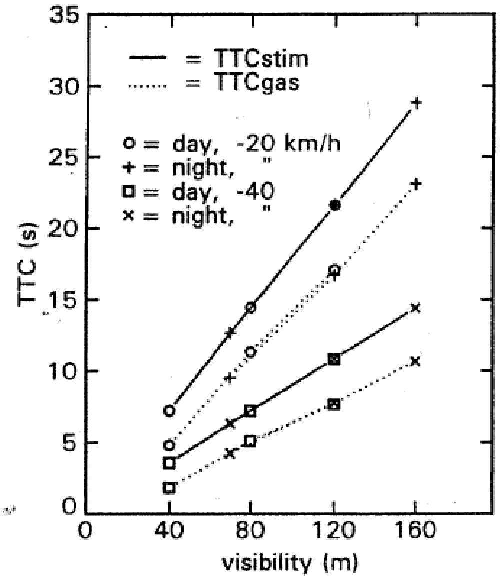
Visibility distances used were 40, 80, 120 and 600 m, according to the standard MVR visibility definition, e.g. White & Jeffery (1980). Since at night, the rear lights of a vehicle are visible over a larger distance than the contour or the road outline following the definition of MVR, the rear lights of the lead vehicle were made visible over a larger distance according to the results of Heiss (1976). In each run, subjects were partly free driving (i.e. no lead cars) and partly in car-following situations with varying speeds. To prevent overtaking, the left lane of the freeway was closed by means of diagonally striped workzone panels.

The *free driving* speeds as found in the simulator experiment reveal a good resemblance with real-world data in good and very poor visibility. In moderate visibility, speeds in the simulator appear to be somewhat lower. Driver's high expectancy of a lead vehicle in the simulator and the absence of overtaking possibilities due to the working zone situation may well explain this difference.

The relevant cue in *approaching* a lead vehicle may be TTC: in the simulator the lead vehicles would become visible at the determined visibility distance, whereas the speed difference was either 20 or 40 km/h. From these visibility distances and speed differences the corresponding TTC values can be calculated, represented by TTC_{stim}. In the night conditions, TTC_{stim} values were larger since, with an equal speed difference, the visibility distance (of the rear lights) was larger. Fig. 9 gives a comparison of TTC_{stim} and TTC_{gas}, being the TTC at the moment the subject fully releases the gas pedal for the first time after the lead car has become visible.

The finding that the TTC_{gas} curves in the night condition coincide with the daytime curves if the different visibility distances for vehicle contours and rear lights are taken into account, indicates that at night subjects already react to the lead vehicle before its contour becomes visible. Their first reaction is based on the extra visibility range provided by the rear lights. Apparently, TTC_{gas} is mainly determined by whatever becomes visible first.

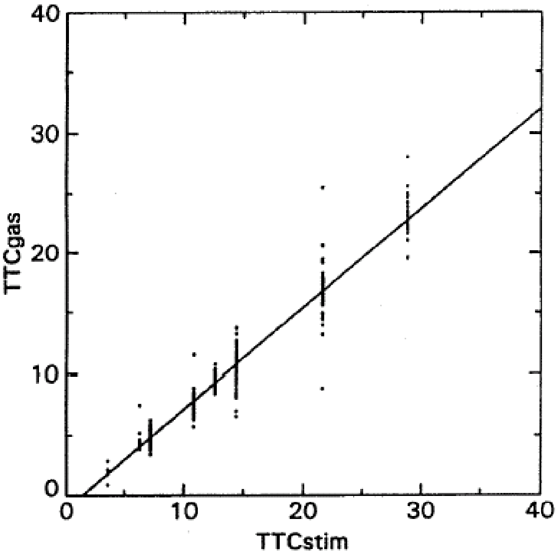
Fig. 9 TTC_{gas} as compared to TTC_{stim} as a function of visibility, light condition, and relative speed.



The relationship between TTC_{gas} and TTC_{stim} can be described well by a linear regression line ($r = 0.97$, $p < 0.0001$) of the following form (Fig. 10):

$$TTC_{gas} = -1.15 + 0.83 * TTC_{stim} \tag{1}$$

Fig. 10 TTC_{gas} as a function of TTC_{stim}, according to Eq. (1).



Similar results were obtained for TTC_{min}, the minimum TTC value as reached during the whole approach phase (Hogema & van der Horst, 1993b). Eq. (2) gives the linear relationship between TTC_{min} and TTC_{stim} ($r = 0.92$, $p < 0.0001$).

$$TTC_{min} = -2.58 + 0.80 * TTC_{stim} \tag{2}$$

TTC_{min} and TTC_{gas} also linearly relate ($r = 0.93$, $p < 0.0001$):

$$TTC_{min} = -1.43 + 0.96 * TTC_{gas} \tag{3}$$

4 DISCUSSION AND CONCLUSIONS

Several studies on Traffic Conflicts Techniques have shown that Time-To-Collision (TTC) is an effective measure for rating the severity of conflicts. In general, only encounters with a minimum TTC less than 1.5 s are considered critical and trained observers appear to operate rather consistently in applying this threshold value in real traffic. Whereas TTC_{min} indicates how imminent a collision actually has been during the approach process, TTC at the onset of braking (TTC_{br}) represents the available manoeuvring space at the moment the evasive action starts. The results of a field experiment where subjects approaching a stationary object with a given speed where instructed to start braking at the latest moment they thought they could stop just in front of the object (van der Horst, 1990; 1991), revealed that both the decision to start braking and the control of braking may well be based on TTC information as directly available to the driver from the optic flow field. This TTC information is an important cue for the driver in detecting potentially dangerous situations. The study by Van der Horst (1990) provided values for both TTC parameters that have to be regarded as minimum values that should be avoided in normal traffic conditions. Together with an 1.5 s reaction time (including the time needed for moving the foot from the gas to the brake pedal), an average TTC_{br} of 2.5 s would result in a TTC-criterion of at least 4 s for activating a Collision Avoidance System (CAS). Tests with different CASs reveal that a CAS with this 4 s TTC-criterion, in combination with a system action to the driver via an active gas pedal, reduces the percentage of small headways considerably without having contra-productive effects on other behavioural measures (Janssen & Nilsson, 1990; Janssen & Thomas, 1993). Apparently, a criterion based on TTC seems most in line with what drivers expect to get from a CAS. So far, only one criterion value has been tested and the question arises whether it would be worthwhile to try other TTC-criterion values as well.

Recently, some studies on driver behaviour in fog, both in real traffic and in a driving simulator (van der Horst et al, 1993; Hogema & van der Horst, 1993a; 1993b), provided a more precise description of critical approach situations. Given a slower lead vehicle that becomes visible at the visibility distance, TTC values are well defined. Since drivers have adapted their speed (at least partly) to the visibility conditions, driving situations in fog may enable information on what criterion values for TTC should be used. Based on an analysis of inductive loop data at an individual vehicle level in various visibility conditions, Hogema and Van der Horst (1993a) conclude that in fog driving speeds are considerably reduced, but that, especially in the visibility range between 40 and 120 m, free-driving speeds are too high to allow for a successful stop for a stationary object. Drivers' speed choice seems more in line with expecting only (slower) moving vehicles ahead. In fog, TTC values tend to increase whereas following distances decrease. Since in the case of car-following TTC equals the following distance divided by the speed difference, this clearly indicates that speed differences between successive vehicles are reduced in fog. Apparently, drivers pay more attention to the car-following task. In addition to this study in actual traffic, Hogema and Van der Horst (1993b) also conducted a driving-simulator study on car-following behaviour in both good and adverse visibility conditions (day/night, fog) with a visibility range between 40 and 600 m. A given visibility distance together with a 20 or 40 km/h slower driving lead vehicle, results in a well-defined TTC value at the moment a lead vehicle becomes visible (TTC_{stim}). So, in this way given TTC values can be presented to a subject in a realistic setting. When comparing TTC_{stim} with TTC at the moment the gas pedal is fully released (TTC_{gas}), it appears that TTC_{gas} can be described well by a linear function of TTC_{stim} (see Eq. (1)). The same yields for TTC_{min} as reached during the approach phase (see Eq. (2)). The finding that TTC_{min} increases with TTC_{stim} implies that drivers include an additional safety margin when they have the opportunity to do so. When they are asked to apply a minimal margin as in the study by Van der Horst (1990), a more or less constant TTC_{min} of 1.1 s results.

For determining a proper criterion setting for a CAS, it would be of interest to combine these relationships with earlier findings with respect to critical TTC_{min} values, e.g. the 1.1 s value as found in the study on TTC and driver's decision-making in braking, and the 1.5 s to distinguish critical from normal behaviour in Traffic Conflicts studies (van der Horst, 1990). By applying Eq. (2), these critical TTC_{min} values would result in a TTC criterion for activating a CAS of about 4.5 and 5 s, respectively.

Based on the results of the first tests with CASs, it is concluded that for defining an appropriate criterion for activating a CAS, the TTC approach is a promising one. The results of the studies on driving behaviour in adverse visibility conditions reveal that, apart from a 4 s TTC criterion, it is worthwhile to investigate a TTC criterion in the range of 4.5 to 5 s as well. For driving in fog as an important application area of CASs, special attention should be given to the distance range between 40 to 120 m.

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