DRIVER BEHAVIOR IN CAR-FOLLOWING: A DRIVING SIMULATOR STUDY

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ABSTRACT: This paper describes the results of a study performed with the interactive fixed-base driving simulator of the Inter-University Research Center for Road Safety aimed: a) at analyzing the driver behavior in car-following situations in different traffic-flow conditions and b) at providing the first elements to choose the most appropriate threshold value of Time-To-Collision (TTC) in order to discriminate unsafe from safe car-following behaviors. A test alignment 8.5 km long and 4 different traffic scenarios were implemented in the simulator. Thirty-two subjects drove in the simulator. Several values of threshold were used to quantified advanced TTC-based indicators. The results highlighted that: 1) the car-following behavior is significantly affected by the volume-to-capacity ratio; 2) the most efficient threshold values of TTC seem to be 2.5 and 3s. These results should be considered for the development of Collision Avoidance Systems.

1 INTRODUCTION

In order to assist the driver in the driving task and improve safety as well as enhance comfort and performance, the modern vehicles are equipped with advanced driver assistance systems. Among the driver assistance systems believed most efficient are the Collision Avoidance Systems (CAS). An important component of Collision Avoidance Systems is the collision warning, which provides alerts intended to assist driver in avoiding rear-end crashes. The goal of the collision warning is to allow the driver enough time to avoid the crash, and yet avoid annoying the driver with alerts perceived as occurring too early or unnecessary. As matter of fact, early warning can be interpreted as nuisance alarm and, thus, desensitize the driver to future system warnings. Therefore it is essential to define a warning strategy based on the effective driver behavior in order to avoid rear-end crashes and false alarms. That gives rise to the necessity of discriminating unsafe from safe car-following behaviors. The unsafe behavior are usually distinguished on the basis of threshold values of indicators which had been suggested by the scientific literature for evaluating rear-end collision risk. Among these the most efficient are believed the Time-To-Collision (TTC) [1]) [2] [3] [4] [5] and the most advanced TTC-based safety indicators [6]) [7]) (see next section background). Such advanced indicators are usually quantified using traffic micro-simulation models. Concerning this topic the literature highlights two main issues. The first one concerns the appropriate choose of the critical value of TTC in order to distinguish unsafe approach conditions from the ones considered safe. As a matter of fact, a survey of the literature (see background) reveals that there is no univocal threshold value for distinguishing unsafe car-following maneuvers. The second issue concerns the use of the microscopic simulation models (more specifically car-following models). If on one hand, these models allow us to describe the process of one vehicle following another vehicle in the same lane, on the other, they are not able to realistically reproduce the driver's behavior. The latter in fact, notwithstanding the many factors from which it depends, is modeled through a series of parameters whose values are purely statistical.

The present study tries to give a contribution on this matter. More specifically, it is aimed at analyzing the driver behavior in car-following situations in different traffic-flow conditions and at providing the first elements to choose the most appropriate threshold value of TTC. Therefore an experimental study using the Inter-University Research Center for Road Safety (CRISS) interactive fixed-base driving simulator was conducted in order to quantify, based on the effective behavior of the a sample of drivers in the driving simulator, the advanced TTC-based indicators.

It should be noted that interactive driving simulators are considered useful and reliable tools to assess driver behavior induced by the effective geometric configurations and traffic interference. They allow a high degree of realism, a great versatility on reconstructing roads, an easy data collection, the highest safety for test drivers and the possibility of carrying out experiments in controlled conditions (weather, traffic, and drivers). The driving simulators are also able to render the visual perception process that a driver uses to perceive the relative motion that is established in a car-following situation, or more in general, in the vehicle interactions [8]. For such benefits driving simulation systems have been widely applied beneficially in road safety analyses (for exhaustive references see [9]). Moreover several validation studies of simulators (some of these validation studies refer to the driving simulator used in the present study), carried out in different driving conditions [9] have ensured us sufficient guarantees of the reliability of the data recorded in the driving simulators. The research was developed through the following steps:

- a driving simulator study (design of a test alignment and following implementation in the driving simulator, definition and implementation of traffic scenarios, driving test and data collection);
- calculation of TTC-based safety indicators for the measurement of risk adopted by the driver in a car-following condition;
- analysis of the relationship between the safety indicators and volume-to-capacity ratio to discuss the car-following behavior and give the first elements to define the most appropriate threshold value of TTC.

2 BACKGROUND

2.1 Time To Collision-based indicators

The Time-To-Collision notion was introduced in 1972 by the Hayward [10] and afterwards applied in different studies aiming at evaluating the rear-end collision risk. Time-To-Collision represents the time required for two successive vehicles, occupying the same lane, to collide if they continue at their present speed until the moment of the crash when vehicle (i) moves faster than preceding vehicle (i – 1):

$$\mathrm{TTC}_{\mathrm{i}} = \frac{\mathrm{x}_{\mathrm{i-1}}(\mathrm{t}) - \mathrm{x}_{\mathrm{i}}(\mathrm{t}) - \mathrm{l}_{\mathrm{i}}}{\dot{\mathrm{x}}_{\mathrm{i}}(\mathrm{t}) - \dot{\mathrm{x}}_{\mathrm{i-1}}(\mathrm{t})} \tag{1}$$

where denotes speed, x the position and l the vehicle length.

The higher a TTC-value, the safer a closing-in situation is.

In order to distinguish unsafe approach conditions from the ones considered safe, we need to establish a threshold value (TTC*), also called a critical value, for the TTC.

Several threshold values are suggested in literature. For example, Hayward [10] suggested that 4 seconds was the TTC level at which a vehicle can have crash risk. Van der Horst [2] for the developing of the Collision Avoidance Systems ascertained the effectiveness of warning strategy based on a threshold of TTC equal to 4 s. Hirst and Graham [11] and Brown et al. [12] suggested that the TTC threshold be set to 3 s for developing of Rear-End Collision Avoidance Systems. Hogema and Janssen [13] studied the driver behavior at an approach of a queue and found a TTC threshold value of 2.6 s. Van Der Horst [14] reported even lower critical TTC values, based on approaches at intersections.

In order to assess the risk associated with car-following maneuvers two advanced safety indicators, based on the Time-To-Collision notion, were proposed in scientific literature by Minderhoud and Bovy [6]: Time Exposed Time-to-collision (TET) and Time Integrated Time-to-collision (TIT). The TET indicator expresses the total time spent in safety critical situations, characterized by TTC-value below the threshold value TTC*. For calculation purposed, it is assumed that the TTC, at an instant t, is kept constant for a small time step τsc. For the considered time period H, there are T = H/τsc time instants, to which the summation is extended while calculating the TET value. For each driver i we have:

$$\mathrm{TET}_{\mathrm{i}}^{*} = \sum_{\mathrm{j=1}}^{\mathrm{T}} \delta_{\mathrm{j}}(\mathrm{t}) \cdot \tau_{\mathrm{sc}}\,, \qquad \delta_{\mathrm{j}}(t) = \begin{cases} 1 & \forall\ 0 \le TTC_{i}(t) \le TTC^{*} \\ 0 & else \end{cases} \tag{2}$$

The superscript * indicates that the parameter has been calculated with respect to a prefixed threshold value.

The TIT indicator, evaluating the entity of the TTC lower than the threshold, allows to express the severity associated to the different conditions of approach that take place in time; for each driver i we have:

$$\mathrm{TIT}_{\mathrm{i}}^{*} = \sum_{\mathrm{j=1}}^{\mathrm{T}} \left[\mathrm{TTC}^{*} - \mathrm{TTC}_{\mathrm{i}}(\mathrm{j})\right]\tau_{\mathrm{sc}}\,, \qquad \forall\ 0 \le \mathrm{TTC}_{\mathrm{i}}(\mathrm{j}) \le \mathrm{TTC}^{*} \tag{3}$$

The calculation modalities for the two indicators are illustrated in figure 1. The TTC profile over time for vehicle i in the figure is displayed for five closing-in situations; three of these become safety critical because TTC-value below the threshold value TTC* (horizontal line) were collected. The TET indicator for the vehicle i is the sum of the time travelled over the considered time period H with subcritical TTC-value; the TIT indicator is the sum of the shaded areas.

It should be noted that the Time-To-Collision-based safety indicators for the single driver are calculated considering a specified time period (then for a certain road length); instead TTC refers to the condition in a single instant t (or in a single cross-section). Therefore TETi and TITi allow us to obtain the car-following behavior, in terms of total time spent in safety critical situations and severity, of a single driver along the road.

Such safety indicators are used for the present study.

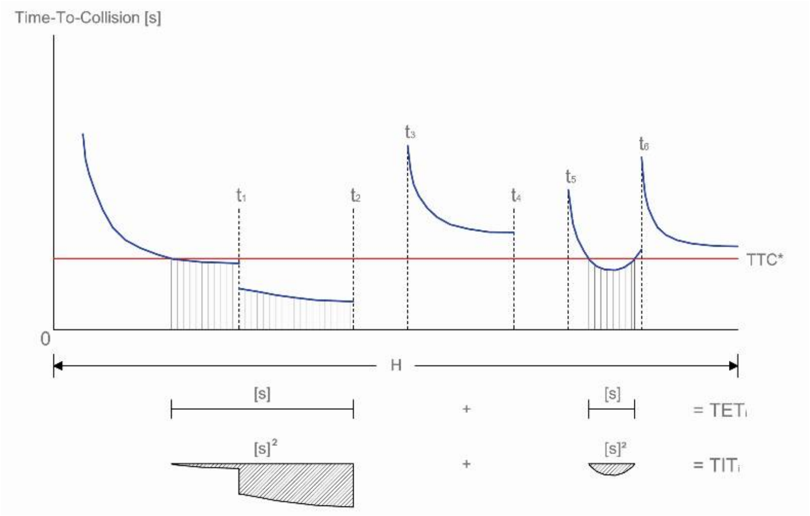


Fig.1. Time-To-Collision profile and corresponding TTC-based safety indicators

3 METHOD

3.1 Driving simulator study

3.1.1 CRISS driving simulator

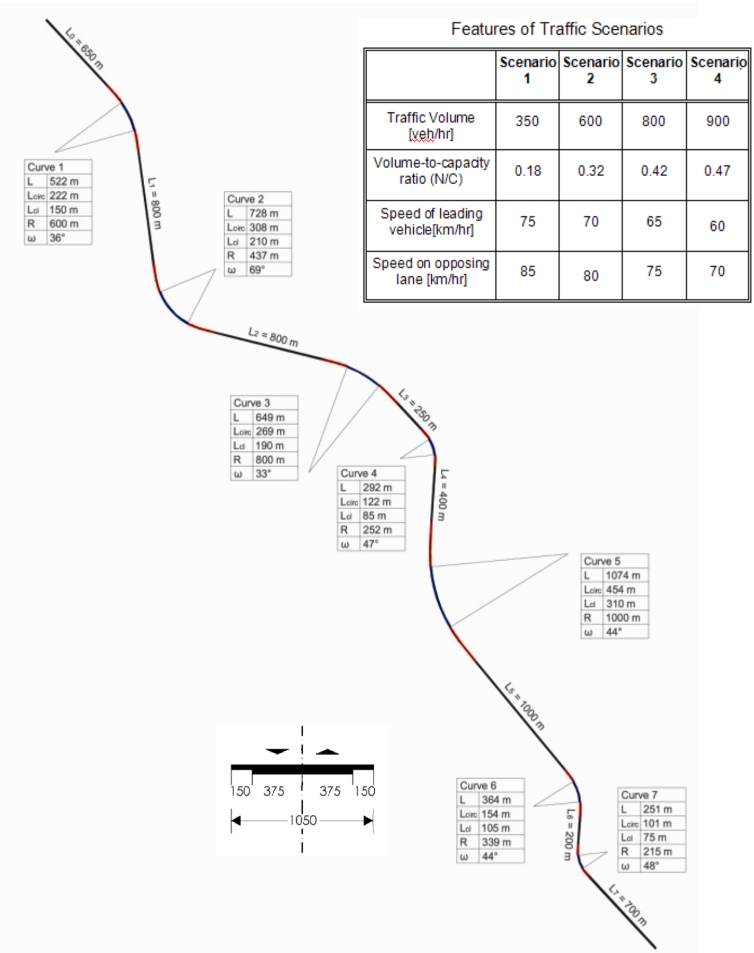
The CRISS simulation system is an interactive fixed-base driving simulator. It includes a complete vehicle dynamics model based on the Non Linear Vehicle Dynamics Analysis computer simulation. The model has been adapted to run in real time and it has been validated extensively [15]. The hardware interfaces include a steering wheel, pedals and a gearshift lever. They are mounted on a real vehicle in order to reproduce a realistic driving environment. The driving scene is projected onto three screens, one in front of the vehicle and two on each side. The usual field of view is 135°. The scenario is updated dynamically in accordance with the traveling conditions of the vehicle, which depend on the actions of the driver on the pedals and the steering wheel. The system is also equipped with a sound system reproducing the sounds of the engine. This set-up provides a realistic view of the road and surrounding environment.

The system offers the possibility to implement a myriad of traffic scenarios in terms of kinds of vehicles (passenger cars, trucks, motorcycles, etc..), numbers of vehicles per lane, speeds and paths of each vehicle. The system allows us to record the intensity of drivers' actions on the brake, accelerator pedal, and steering wheel and provides us with many parameters describing traveling conditions (vehicle barycenter, relative position in relation to the road axis, local speed and acceleration, steering wheel rotation angle, pitching angle, rolling angle, etc.). Moreover it allows us to record the headway in terms of time and distance from the vehicle head as well as time and distance from the vehicle in the opposite direction. All the data can be recorded at time or space intervals respectively of a fraction of a second or of a meter. Figure 2 shows a phase of a driving.

Fig.2. CRISS Driving Simulator: phase of the experiment

3.1.2 Test alignment

A two-lane rural road of about 8.5 km was designed and implemented in the driving simulator. The alignment had a cross-section 10.5 m wide. Lane and shoulder widths were 3.75 m and 1.5 m respectively. In order to eliminate any possible influences of the profile on the driver's behavior, the road alignment was designed without longitudinal grades. The alignment had 15 different geometric elements: 8 tangents with length ranging between 200 m and 1000 m; 7 horizontal curves made up of approach clothoid, circular curve and departure clothoid. The radii of the circular curve ranged between 215 m and 1000 m. The traffic was introduced in both directions in order to simulate four different volume-to-capacity ratios. Figure 3 shows the geometric characteristics of the alignment and the features of traffic concerning the four scenarios. The features of the test alignment and the traffic volumes establish a volume-to-capacity ratio, estimated from traffic volume (N) and capacity of the road (C), ranging between 0.18 and 0.47. These traffic densities correspond to the Level-of-Service A (scenario 1), B (scenarios 2 and 3) and C (scenario 4).



Features of Traffic Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Traffic Volume [veh/hr]	350	600	800	900
Volume-to-capacity ratio (N/C)	0.18	0.32	0.42	0.47
Speed of leading vehicle[km/hr]	75	70	65	60
Speed on opposing lane [km/hr]	85	80	75	70

Fig.3. Geometric features of test alignment and traffic scenarios

3.1.3 Procedure and participants

The study was carried out using dry pavement conditions in good state of maintenance, simulating the characteristics of a medium-class car, both as regards size and mechanical performance, with automatic gear-changes. The data recording system was set to acquire all the parameters at spatial intervals of 5m.

The driving procedure was broken down into the following steps: 1) communicating to the driver about the duration of the driving and the use of the steering wheel, pedals, and automatic gear; 2) training in the driving simulator on a specific alignment for approximately 10 min to allow the driver to become familiar with the simulator's control instruments; 3) the execution of two test scenarios in the established sequence; 4) the driver vacating the car for about 5 minutes in order to re-establish psychophysical conditions similar to those at the beginning of the test and filling in a form with personal data, years of driving experience, average annual distance driven; 5) the execution of the two remaining test scenarios in the established sequence; 6) filling in of an evaluation questionnaire about type (nausea, giddiness, daze, fatigue, other) and entity (null, light, medium, and high) of the discomfort perceived during the driving. The sequence of the four scenarios was varied for each driver in order to avoid influences due to the repetition of the same order in the experimental conditions. The participants were left free do chose their own headways.

The driving in the simulator was performed by 32 drivers with ages ranging from 22 to 40, male (70%) and female (30%), with a driving experience of at least 3 years and an average annual driven distance on rural roads of at least 2500 km. No participant experienced any high or medium level of discomfort, 13 and 19 elements experienced the light and null level of discomfort respectively. Therefore no participant was excluded from the sample.

3.2 Data processing

The data collected during the simulated drives were processed in order to obtain the quantification of the safety indicators (TET and TIT). As previously mentioned, there is no univocal threshold value of the TTC in according to which the two TTC-based safety indicators are calculated in current scientific literature. Such indicators were consequently calculated according to the four threshold values of the TTC, which are the most frequently suggested in literature: 2, 2.5, 3 and 4 seconds. The TET and TIT indicators for each driver were determined for each traffic scenario and threshold value. Such values referred to the entire test alignment. The average values of the indicators TET and TIT recorded for 32 drivers on the entire test alignment were then quantified (Table 1).

Table.1. TETav and TITav in different traffic conditions and for different threshold values TTC*

TTC*	SCENARIO 1		SCENARIO 2		SCENARIO 3		SCENARIO 4	
	TET_{av} [s]	TIT_{av} [s^2]	TET_{av} [s]	TIT_{av} [s^2]	TET_{av} [s]	TIT_{av} [s^2]	TET_{av} [s]	TIT_{av} [s^2]
2	0.27	0.06	1.45	0.76	1.09	0.67	0.65	0.27
2.5	1.45	0.46	3.04	1.88	2.00	1.41	1.63	0.81
3	3.58	1.69	5.63	3.99	3.23	2.72	3.38	1.93
4	10.78	8.73	13.94	13.57	7.01	7.65	9.37	7.87

4 RESULTS AND DISCUSSION

4.1 Driver's behavior in car-following and the most efficient threshold value of Time-To-Collision

In order to analyze how the traffic affects driver behavior in car-following situations, the average values TETav and TITav were correlated to the corresponding volume-to-capacity ratio (N/C). The diagrams in Figure 4 show how the two safety indicators vary according to the volume-to-capacity ratio.

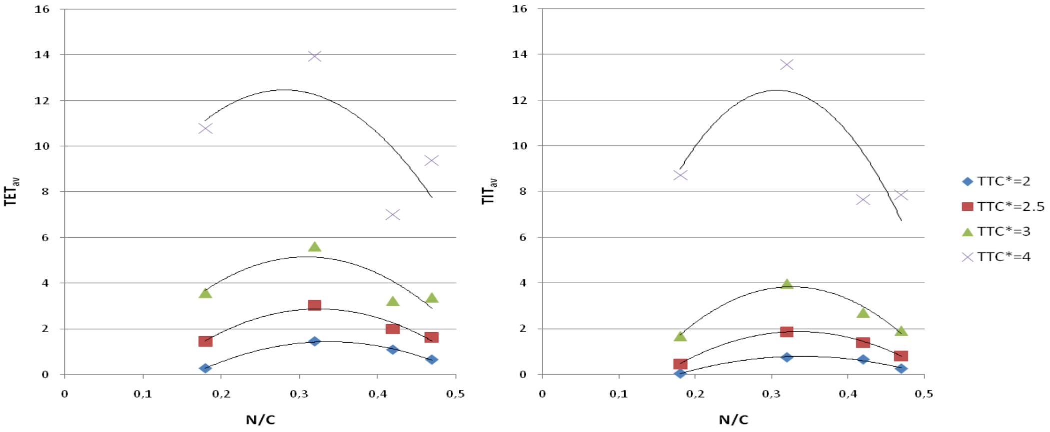


Fig.4. TETav and TITav for different volume-to-capacity ratios

In both diagrams, the relationship between the two variables that gave the value of the coefficient of determination closest to 1 was a quadratic model. The trend of TETav and TITav with the increase of volume-to-capacity ratio consequently increases initially and thereafter decreases as soon as the maximum value is reached. In particular, the maximum values of both indicators are given for a medium-flow traffic condition, similar to the one characterizing the second traffic scenario. In such a condition, the traffic interference on one hand spurs the driver to overtake the lead vehicle, while the other, makes safely carrying out the passing maneuver difficult. This difficulty is due to vehicles in the oncoming traffic lane. Nonetheless, traffic in the oncoming lane does not reach levels which are so high as to induce the driver to definitively renounce the overtaking maneuver. The driver consequently assesses the possibility of carrying out the overtaking and should the maneuver be deemed less than totally safe, he tags behind the slow moving vehicle ahead of him from a very short distance, while waiting to perform the overtaking maneuver whenever it shall be deemed possible. The driver consequently places himself in a car-following condition which is risky whilst carrying out such a complex activity.

This risky condition arises to a lesser degree as far as lower volume-to-capacity ratio is concerned, when the overtaking maneuver is rendered a great deal easier owing to greater headway afforded by the vehicles in the opposite direction. The time which is therefore spent behind the slow vehicle, whilst waiting to carry out the overtaking maneuver, is substantially reduced compared to that spent in the medium-flow traffic condition. Finally, with a higher volume-to-capacity ratio, the remarkably low headway between the vehicles in the oncoming traffic lane and the consequent low passing gap precludes the driver from attempting the maneuver at all. The driver, in most cases therefore, renounces the overtaking maneuver, deeming this to be quite difficult, and remains at a due distance from the slow vehicle ahead.

An addition note can be made concerning the increasing dispersion of data shown in figure 4 when the threshold value of Time-To-Collision (TTC*) increases. The threshold value of Time-To-Collision has the precise role of distinguishing safe and safety-critical approach situations. For the threshold of 4 s the values of TTC-based indicators are higher than those obtained for lower threshold values. Nevertheless, this does not ensure that the car-following maneuvers which give rise to such higher values of TTC-based indicators are actually hazardous maneuvers. In other words, the 4 s TTC*-value seems to be excessively cautious and hence produces false alarms. A plausible reason for the greater dispersion of data might be the weaker correlation between the car-following maneuvers (some of which not genuinely risky) and the volume-to-capacity ratio. On the other hand, the threshold of 2 s appears be too low in order to collect all the truly risky car-following maneuvers. The use of TTC* equal to 2 s does not ensure that all the genuinely risky maneuvers are included in the assessment of rear-end collision risk. The threshold of 2 s hence makes the exhaustiveness of risk evaluation questionable. Therefore to distinguish unsafe car-following maneuvers the most efficient values of threshold of TTC seem to be 2.5 and 3 s.

5 CONCLUSIONS

The experimental study at the CRISS driving simulator revealed the following main results. The most advanced TTC-based indicator, which allow us to evaluate the car-following behavior of the driver along the road, increase as volume-to-capacity ratio increases, and then decrease as soon as the maximum value is reached. In particular, the maximum values of TETav and TITav indicators are given for a medium traffic-flow condition. This result appears to be due to the fact that the traffic in the oncoming traffic lane does not reach levels which are so high as to induce the driver to definitively renounce the overtaking maneuver. The driver consequently follows only a very short distance behind the slow moving lead-vehicle, while waiting to perform the overtaking maneuver whenever it might be deemed possible. During this complex activity drivers adopt an unsafe car-following position.

Concerning the more effective threshold value of TTC among those suggested in literature for identifying genuinely risky car-following maneuvers, the data of TTC-based indicators showed that the value of 4 s seems to be excessively cautious. It might produce false alarms. On the other hand, the threshold of 2 s seems to be too low in order to collect all the effectively risky car-following maneuvers. The use of TTC* equal to 2 s does not ensure that all the genuinely risky maneuvers are included in the evaluation of the rear-end collision risk. The most efficient threshold values of TTC were considered to be 2.5 and 3 s.

Further researches, actually ongoing at the CRISS Simulation Laboratory, are aimed to ascertain the variability of the threshold value of TTC for different average speed of the driver as well as to analyze the car-following behavior when the subjects drive vehicles equipped with several Collision Avoidance Systems.

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