

TRden 18125

**A TIME-BASED ANALYSIS
OF ROAD USER BEHAVIOUR
IN NORMAL AND CRITICAL ENCOUNTERS**

Stellingen/Propositions

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Delft, April 1990

STELLINGEN

1. Het naderen van een kruispunt en het afwikkelen van ontmoetingen met ander verkeer spelen zich af volgens tamelijk vaste gedragspatronen, die zich goed laten beschrijven in termen van tijdmaten zoals Time-To-Intersection en Time-To-Collision.

Dit proefschrift

2. Normale en kritische ontmoetingen in het verkeer kunnen goed van elkaar onderscheiden worden door als criterium een minimum waarde voor Time-To-Collision te hanteren.

Dit proefschrift

3. Time-To-Collision zoals direct beschikbaar uit het visuele stroomveld speelt een sleutelrol bij het detecteren van potentieel gevaarlijke situaties in het verkeer.

Dit proefschrift

4. Bij het naderen van een voorrangsweg met vrijliggende fietspaden ziet men het fietspad gemakkelijk over het hoofd en daarom zijn speciale maatregelen nodig om de aandacht op het fietspad en zijn gebruikers te richten.

5. Een voertuigafhankelijke verkeerslichtenregeling vermindert weliswaar het aantal 'gelegenheden' om door rood te rijden aanzienlijk, maar beïnvloedt de roodlicht-discipline op zich nadelig.

6. De verkeersveiligheid bij bruggen en spoorwegovergangen kan verbeterd worden door aan de signalering een ontruimingsfase met continu geel toe te voegen en als stopsignaal continu rood toe te passen.

7. Het baseren van uitzichtdriehoeken op kruispunten op de tijd nodig om te stoppen is onjuist en onnodig kostbaar.

o.a. Hakkesteeft, P. (1985). Functionele eisen wegen en kruispunten. Postacademische cursus "Ontwerpen van wegen en kruispunten; meer met minder geld".

Lay, M.G. (1988). Update for Handbook of Road Technology, Australian Road Research Record (18), no. 3.

8. Wegen voor doorgaand verkeer, zoals op stadsplattegronden aangegeven en in verkeerscirculatieplannen opgenomen, zouden meer dan nu voor de weggebruiker als zodanig herkenbaar moeten zijn.

9. Bij het terugdringen van het autogebruik zou het daadwerkelijk gebruik van de fiets expliciet moeten worden beloond.

10. Door de toenemende mate van luchtverontreiniging kunnen bij de leuze: "Fietsen is gezond" vraagtekens worden geplaatst.

11. Het getuigt van visie als economische nulgroei als uitgangspunt wordt genomen om de huidige roofofbouw op het leefmilieu te stuiten.

12. De verwarring en onduidelijkheid over 06 nummers had eenvoudig voorkomen kunnen worden door gratis en niet-gratis nummers niet met dezelfde twee cijfers te laten beginnen.

PROPOSITIONS

1. Drivers approaching an intersection and dealing with encounters with other road users display rather consistent behavioural patterns that can be described well in terms of time measures such as Time-To-Intersection and Time-To-Collision.

This dissertation

2. Normal and critical traffic encounters can be distinguished well by applying a minimum value of Time-To-Collision as a criterion.

This dissertation

3. Time-To-Collision as directly available from the optic flow field is an important cue in detecting potentially dangerous situations in traffic.

This dissertation

4. At intersections with separate cycle tracks along the main road, the cycle track is easily overlooked; therefore, special provisions are needed to direct drivers' attention to the cycle track and its users.

5. Although a vehicle-actuated traffic signal control considerably reduces the number of 'occasions' to run the red light, the discipline at the red light per se appears to be less than for fixed-time controlled signals.

6. The traffic safety at draw-bridges and railway grade crossings can be improved by including a clearing-interval with a steady yellow signal and by applying a steady red stop signal.

7. The calculation of intersection stopping sight distances based on the time needed to come to a stop is not correct and unnecessarily expensive.

i.a. Hakkesteegt, P. (1985). Functionele eisen wegen en kruispunten. Postacademische cursus "Ontwerpen van wegen en kruispunten; meer met minder geld".

Lay, M.G. (1988). Update for Handbook of Road Technology, Australian Road Research Record (18), no. 3.

8. Roads for through traffic, as indicated on city maps and included in traffic circulation plans, should be more recognizable as such to the road user than they are now.

9. In reducing car use, the use of the bicycle instead should be explicitly rewarded.

10. Because of the increasing air pollution, the slogan "Bicycling is good for your health" can be questioned.

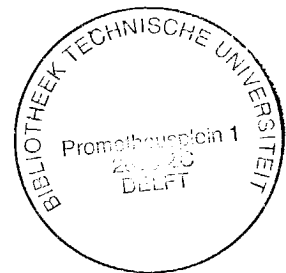
11. It would show vision if economical zero-growth is taken as a starting-point for stopping the current over-exploitation of the environment.

12. The confusion and uncertainty about the 06 numbers could have been avoided simply by not giving free and non-free numbers the same two starting digits.

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**A TIME-BASED ANALYSIS
OF ROAD USER BEHAVIOUR
IN NORMAL AND CRITICAL ENCOUNTERS**

Proefschrift



ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus, prof. drs. P.A. Schenck,
in het openbaar te verdedigen ten overstaan van
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Opgedragen aan mijn ouders

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1 INTRODUCTION

1.1 Aim of the study

Road traffic plays an essential role in transportation; practically no trip can be made without someone somehow or somewhere taking part in road traffic. However, traffic accidents are still a major negative by-product of our current road traffic system. During the nineteen-sixties the heavy increase in the number of motor vehicles resulted in a sharp increase in the number of road accidents. Since 1972 the number of (police-reported) casualties in the Netherlands decreased considerably in spite of a doubling of the number of motor vehicles. However, the current number of accidents is still unacceptably high (about 1,700 fatalities, 90,000 injuries and 600,000 damage-only accidents in 1983, [Directie Verkeersveiligheid, 1986]). Apart from harm and grief to the people involved, the annual costs of traffic accidents are estimated to be Dfl. $6 \cdot 10^9$ in the Netherlands [McKinsey, 1985]. Countermeasures directed at a reduction of the consequences of collisions apparently contributed to a 50% reduction over the last fifteen years in the annual number of people killed in traffic. Examples of these countermeasures are the introduction of seat belts, crush zones in cars, mandatory helmet use for motor and moped riders, and breakaway lampposts. The effectiveness of those measures can be relatively easily estimated from accident statistics, and moreover, accident statistics have an important general monitoring function to make us aware of the extent of the problem.

But the answer to the question of how to prevent accidents is more difficult. For this, a good understanding of the causation process leading to accidents is needed before adequate countermeasures can be proposed. However, the pre-crash phase of accidents can almost never be investigated by direct observation. Reconstructions based on laborious in-depth and on-the-spot accident investigations can give some insight into the causes of accidents, but it appears extremely difficult to quantify and translate findings into recommendations for countermeasures related to road user, vehicle, road, and/or traffic environment [Grayson and Hakkert, 1987]. Moreover, given the present societal need for mobility the traffic safety problem can not be treated in isolation without considering the operational functioning of the system as such and vice versa.

As the major operational deficiencies in the road traffic system are eliminated, research methods for traffic safety improvement have to become more refined, which in turn is increasingly exposing the limitations with the use of accident data for safety analysis. Recently, Hakkert and Hauer [1987] summarised the problems of accident reporting; only a fraction of all accidents is reported, varying over different types of

accidents, road users involved, rural/urban, day/night, etc. Because accidents are relatively rare events in the total traffic process and accident frequencies are unstable in nature [Hauer, 1975], accident counts are an ineffective basis for **detecting** specific traffic safety problems. For the next phases of research into road safety problems, viz. **analysing** and **diagnosing**, defining **remedial** measures and **evaluating** effects, the information available from accident data is mostly inadequate.

Systematic observations of road user behaviour in various traffic situations, ranging from normal encounters, via traffic conflicts to actual collisions, combined with knowledge about human information processing capabilities and limitations, may offer wider perspectives in understanding the causes of safety problems. In particular, the study of conflict behaviour is a natural candidate for that purpose; conflicts are assumed to be strongly related to accidents, their frequency of occurrence is relatively high, and they offer a rich source of information on causal relationships. Therefore, they present a more realistic basis for improving traffic safety than accident counts. Besides, an approach with the potential of preventing at least a part of the accidents should be promoted for ethical reasons.

When analysing behaviour it is important to pay attention to both the similarities and the differences between the processes leading to normal encounters and to critical conflicts.

So, we come to the central question of this study: How can we distinguish normal and critical behaviour of road users, and how is this related to road users' decision-making in traffic? In particular, this study will focus on the analysis of road user behaviour in actual traffic in terms of time related measures, and will examine the hypothesis that road users make directly use of time-based measures as a cue for their decision-making in traffic.

1.2 Outline of the study

Chapter 2 discusses the task of the road user as an information processing system and, consequently, road user behaviour is studied as resulting from processing information, finding its roots in the interaction among road user, vehicle and environment. Following a brief introduction to Traffic Conflicts Techniques, the preference for time related measures is discussed from this point of view.

Chapter 3 discusses some methodological aspects of the video observation technique as developed for this study, a description of time related measures, and a brief survey of several field observation studies, that generated the data for the analysis of road

user behaviour in relationship with both the environment (Chapter 4) and other road users (Chapter 5).

Chapter 6 describes a controlled field experiment that deals with the question whether drivers are able to use Time-To-Collision as a direct cue for their decision-making in braking.

A general discussion of the results, some practical applications, and directions for future research are given in Chapter 7.

Detailed information on procedures and measures of analysis can be found in the Appendices.

2 BACKGROUND

2.1 The task of the road user

In actual road traffic the functioning of the road users is of prime importance for a successful operation of the total system. In order to understand their behaviour, it is necessary to understand how they gather and use information to perform their task. In the literature the task analysis for driving a car is well documented. Basically, a conceptual model of the driving task consists of three hierarchically ordered levels, **navigation**, **guidance** and **control** [Allen et al., 1971]. Tasks at the navigation level refer to the activities related to planning and executing a trip from origin to destination. The need for processing information only occurs occasionally, with intervals ranging from a few minutes to hours. The guidance level refers to tasks dealing with the interaction with both environment (roadway, traffic signs, traffic signals) and other road users. Activity is required rather frequently with intervals of a few seconds to a few minutes. At the control level the motion of the vehicle is controlled in longitudinal and lateral direction. Information has to be frequently processed, ranging from intermittent activities every few seconds to almost continuous control.

In a recent publication, Alexander and Lunenfeld [1986] visualised the relationship between the levels by a set of nested triangles (Fig. 2.1), hierarchically ordered according to dimensions of **complexity** and **primacy**.

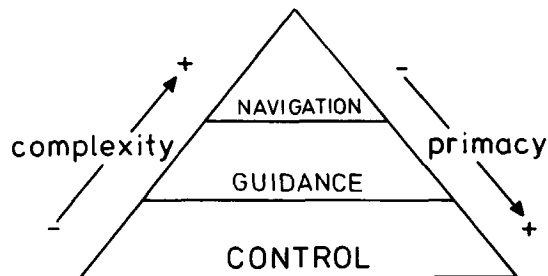


Fig. 2.1 Levels of the driving task.

The complexity dimension indicates that at the control level performance is relatively simple and overlearned and poses a very low demand on the cognitive capacities of the driver, while at the guidance and the navigation level the information handling becomes increasingly complex, and, consequently, puts a much higher demand on cognitive processes. Subtasks between or within the different levels are often competing. The primacy dimension refers to the priority of processing information,

given by the severity of the consequences in case of driver error or an emergency situation. For example, a flat tire or being suddenly confronted with a heavy wind gust will immediately interrupt activities at the navigation level, since getting lost has less severe consequences than running off the road.

At each level of the driving task the successive steps of information processing can be distinguished, i.e. **perception, identification, interpretation, and decision-making**. Each step takes time. At the highest level the decision-making process might be rather complex and needs more processing time than at the control level, where the performance is completely overlearned and actions are executed almost by rote. Furthermore, decisions made at the navigation level serve as input to the guidance level, and the decisions made at the guidance level direct the information processing at the control level, where finally the execution of the resulting decisions is actuated.

For other road users, basically the same task levels of performance can be distinguished as for car drivers, though for pedestrians the task at the control level is limited to the control of locomotion.

2.2 Studying road user behaviour

Both in research on traffic safety problems and in evaluating remedial measures, the usefulness of accident data is very limited. In general, an accident is the outcome of a dynamic process in which a certain combination of various factors results in a collision. Apart from the problem that, generally, accidents are underreported, the information available from police-reported accident records is of little use when it comes to a detailed analysis of the causal chain of events [Grayson and Hakkert, 1987].

In the nineteen seventies several in-depth and on-the-spot accident investigation activities were undertaken by Multidisciplinary Accident Investigation (MDAI) teams in order to collect more detailed and more accurate data. Main success was achieved in improving vehicle design for reducing the outcome of collisions.

A more appropriate approach in preventing accidents seems to be a more detailed study of road user behaviour. The processes that result in near-accidents or serious traffic conflicts have much in common with the processes preceding actual collisions [Hydén, 1987], only the final outcome is different. Advantages of this approach over the mere use of accident data are apparent. Since near-accidents occur more frequently, observation periods can be much shorter which, undoubtedly, is advantageous in evaluation studies. Moreover, the preceding process can be systematically

observed, which is essential for analysing, diagnosing, and solving safety problems. In this approach traffic situations are ranked along a continuum of events ranging from normal situations, via conflicts, to actual collisions. Recently, Hydén [1987] introduced a pyramidal representation of this continuum (Fig. 2.2), clearly visualising the relative rate of occurrence of the different events. An important remaining issue is how to distinguish the various situations systematically and reliably.

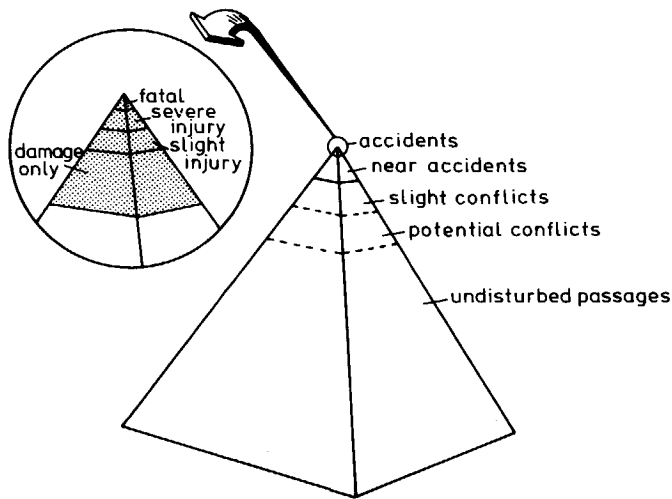


Fig. 2.2 The continuum of traffic events from undisturbed passages to fatal accidents [Hydén, 1987].

Methods for studying road user behaviour show a large variation, ranging from mere observations in actual traffic situations, via the use of instrumented vehicles, to highly controlled laboratory experiments. Which one to use is, among other things, dependent on the level of detail that is required for specific research questions. In analyzing behaviour at the control level of the driving task the use of an instrumented vehicle might be most appropriate, since both the input of information to the driver and the output by the driver to the vehicle are essential. Examples of studies on driver behaviour at the control level can be found in Blaauw [1984], Godthelp [1984], and Riemersma [1987]. For interactions between road users or between road user and environment it is often sufficient or even better to observe the behaviour of road users in terms of the resulting movements of the vehicles. Those can be observed unobtrusively from outside the vehicle in the natural setting of actual traffic situations.

Most studies dealing with interactions between road users only relate to behaviour in conflict situations. In the past, various techniques for observing traffic conflicts have been developed, mostly with individual observers. Following a brief review of these techniques (Section 2.3), Section 2.4 discusses the characteristics of road user behaviour that seem relevant in analysing behaviour in both normal and critical situations.

2.3 Traffic Conflicts Techniques

Traffic Conflicts Techniques (TCT) have been extensively reviewed in the literature [Campbell and King, 1970; Hauer, 1975; Williams, 1981; Kraay, 1983]. Here, only the major steps in the development of TCT's will be discussed.

Although some near accident studies were reported by the end of the fifties [Forbes, 1957], it was by a publication of Perkins and Harris [1967] that the TCT was adopted as an operational tool in road safety research. Originally, their idea was to develop an observation procedure for answering the question whether or not General Motors cars were relatively less involved in unsafe traffic situations than cars of other manufacturers. Soon the potential for a generally applicable observation technique was recognised. Perkins and Harris defined a traffic conflict as any potential accident situation, leading to the occurrence of evasive actions such as braking and swerving. This definition was operationalised by observing the onset of brake lights, lane changes, and traffic violations. The strength of the General Motors TCT lies in its simplicity of application. Although the method was taken up enthusiastically, later studies showed its deficiencies such as the set of conflicts, as defined by Perkins and Harris, appeared to be too large to guarantee a close relationship with accidents [Campbell and King, 1970].

In order to classify the degree of severity of evasive action, Older and Spicer [1976] developed a severity grading of five categories, ranging from precautionary braking or lane change to an emergency action followed by a collision. Individual observers were used, complemented by time-lapse film recordings using two frames per second. According to Older and Spicer, a combined observer and film study is necessary for research purposes, but for a rapid assessment of number and location of conflicts, they conclude the use of individual observers to be sufficient. This conclusion, however, is criticised by Hauer [1978] and Allen et al. [1977]. Firstly, because collisions may occur without any evasive action being taken, the definition of a conflict ought to include those situations as well. Secondly, the grading of severity of the evasive action by observers introduces a subjective element, which can be unpredictable and may only be reduced by a very intensive training programme.

Hayward [1971, 1972] initiated a search for a more objective measure to describe the danger of a conflict situation and concluded that the time-to-collision (TTC) is a dominant one. He defined the time-measured-to-collision (TMTTC or TTC) as: "The time required for two vehicles to collide if they continue at their present speed and on the same path". The minimum TTC as reached during the approach of two vehicles on a collision course is taken as an indicator for the severity of an encounter. Based on a quantitative analysis of 43 situations from film pictures Hayward suggests the use of a minimum TTC value of 1.0 s as a good threshold for defining car-car conflicts. In an evaluation study on road design elements of bicycle routes, Van der Horst [1984a] used a minimum TTC value of 1.5 s as a criterion for defining a conflict between a car and a bicyclist.

For large scale applications a disadvantage in determining the TTC measure objectively is the amount of work involved. Together with making video-recordings on the spot, a time consuming quantitative analysis has to be conducted afterwards. Hydén [1975, 1977, 1987] tried to simplify the method by introducing the time-to-accident (TA), defined as: "The time that passes from the moment one of the road users reacted and starts braking or swerving until the moment that the involved road user had reached the point of collision if both road users had continued with unchanged speed and direction". So, instead of taking the minimum TTC value, as reached during the approach process, Hydén takes the TTC value at the moment the evasive action is started. Hydén had individual observers estimate TA values directly in the field. Originally he proposed one threshold value of 1.5 s [Hydén, 1977] in urban areas. Later he introduced critical values, dependent on speed [Hydén, 1986]. In Section 3.3.1 the Time-To-Collision measure will be discussed in more detail.

Since 1977 an intensive international co-operation in the field of TCT's was started. In several countries various techniques for the systematic observation and/or analysis of traffic conflicts were developed. Large differences in local circumstances resulted in a variety of definitions, observation methods, severity scores, etc. At the first workshop on traffic conflicts techniques at Oslo [Amundsen and Hydén, 1977], a common definition of a traffic conflict was accepted: "A traffic conflict is an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged". After two other workshops, viz. Paris [Older and Shippey, 1980] and Leidschendam [Kraay, 1982], the ICTCT (International Committee on Traffic Conflict Techniques) started in 1983 a joint international calibration study at Malmö, Sweden [Asmussen (Ed), 1984; Grayson (Ed), 1984]. All teams simultaneously made observations at three intersections in Malmö.

In this latter study considerable progress was made in comparing the various techniques (ten countries participated). From a principal components analysis of categorical data it appeared that the variations in scoring mainly resulted from differences in the detection of relevant situations. Once a situation is detected, however, the scores of the various teams can be represented well by a one-dimensional severity scale [Oppe, 1983]. A comparison with objective data, obtained by a quantitative analysis from video [Van der Horst, 1984b], indicated the Time-To-Collision measure to be one of the major factors in explaining this common severity dimension. Along with conflict-type also other aspects of interactions between road users have to be included to explain the relation between Time-To-Collision and severity.

Another objective measure, the Post-Encroachment-Time (PET), as defined by Allen et al. [1977] (see Section 3.3.2) and suggested by Williams [1981] as a promising one, neither correlated with severity nor could it be applied properly for almost one half of the conflicts (mainly because of a full stop by one of the road users involved). It should be mentioned that this rather poor performance of PET refers only to urban areas with mixed traffic. In a second ICTCT calibration study at a rural signalised intersection at Trautenfels, Austria, the PET measure performed better [Oppe, 1986]. This location fits the circumstances, for which the PET originally was intended for.

The validity problem of traffic conflicts techniques always has been a major topic over the years. For a long time the main question was whether conflicts could predict accidents, viz. whether conflict counts could serve as a substitute for accident-counts, and correlation-coefficients were used to prove or to reject the usefulness of traffic conflicts. Hauer [1975, 1978], and recently Hauer and Garder [1986], demonstrated clearly the inadequacies and limitations of this simple approach because of the inherent random nature of accident frequencies (see also Van der Horst and Riemersma [1981]). At most, estimates of the expected number of accidents can be achieved based on the product of the expected number of conflicts and the conditional probability of an accident given a conflict. This approach was applied in a large scale validation study in the USA [Miglez et al., 1985]. The main conclusion of that study was as follows: "Traffic conflicts produce estimates of average accident rates nearly as accurate, and just as precise, as those produced from historical accident data". Apart from this, additional advantages of studying road user behaviour in critical situations were already summarised (section 2.2). For a recent discussion on the validity issue of traffic conflicts techniques the reader is referred to Grayson and Hakkert [1987].

2.4 Characteristics of road user behaviour

The movements of road users relative to those of other road users or relative to the environment can be described in various ways. For studying interacting behaviour the kinematic equations of motion in relation to a fixed coordinate system seem to be the basis from which to start. From the trajectories of individual road users (i.e. successive positions in time), basic variables such as distance, velocity, and acceleration can be derived.

In most Traffic Conflicts Techniques the severity of traffic conflicts (partly) reflects the proximity to an actual collision. This proximity can be defined as either the distance in space or the distance in time between two road users. Moreover, the intensity of the evasive action (braking and/or swerving) is an important factor in determining the severity of traffic conflicts. The problem with both the distance in space and the intensity of the evasive action is that they have to be combined with at least one other factor in order to be useful in defining the severity of a conflict. A small minimum distance between two road users does not necessarily mean that the interaction also was very close to an actual collision. That depends more on how that small distance was reached. In the case of two vehicles on a perpendicular course, for example, the situation where a given minimum distance is reached after an emergency type of braking is quite different from the one where two vehicles are passing each other at that given minimum distance without any actual collision course. Also the intensity of evasive action has to be related to the necessity to avoid a collision. Another problem might be how to grade evasive actions consisting of both braking and swerving. A definition of proximity based on distance in time such as the TTC measure seems to be advantageous because it combines several aspects of the dynamic interactive process into one variable. In Section 3.3 some time-related measures will be discussed in more detail.

Another advantage of describing road user behaviour in terms of time measures seems to be that it enables a more general approach to the problem of how one switches between the different levels of the driving task (primacy). Especially at intersections several tasks will interfere. The most promising common dimension along which the subtasks can be described seems to be time. Godthelp [1984] developed a Time-to-Line Crossing (TLC) approach as a description of the driving strategy in lateral positioning at the control level. In principle, the approach by modelling driving as a supervisory control task [Blaauw, 1984] enables a multi-task analysis in which driving is considered to be a time-management task.

2.5 Conclusions

A conceptual model of the task of the road user consists of the three levels navigation, guidance, and control, ordered hierarchically according to the dimensions of complexity and primacy. However, in the literature these dimensions are described only in general terms. Especially at intersections, where the levels are often competing, primacy is of utmost importance. A description of each task in terms of time-related measures seems to have potential for defining primacy more explicitly. Moreover, a direct link with the time each successive step in human information processing takes might be made.

Various traffic conflicts techniques at least partly use a time-related measure such as Time-To-Collision or Post-Encroachment-Time for defining the severity of traffic conflicts. However, the threshold values used appear to be mainly intuitively determined instead of based on systematic research. Highly trained observers appear to be able to operate rather consistently in detecting and classifying serious conflicts. But in the transition area between normal encounters and conflicts observer subjectivity becomes increasingly important. Because in this study the emphasis will be on a detailed analysis of road user behaviour in both normal and critical situations, the use of individual observers is rejected and it is considered essential to develop an objective observation and analysis method enabling a quantification of relevant characteristics of interactions with other road users or with the environment.

3 METHODOLOGICAL ASPECTS

3.1 Introduction

When road users' interacting behaviour in actual traffic situations has to be studied in detail accurate registration and analysis techniques have to be used. The development of a quantitative method for analysing road traffic scenes started by comparing film and video techniques. Both techniques have their specific advantages and limitations, but with respect to costs, practical aspects, and potential for future technological developments the use of video was and still is to be highly preferred (Van der Horst and Sijmonsma, 1978). A semi-automatic procedure for analysing video scenes was developed, enabling a quantification of movements of any given vehicle in actual traffic.

A brief description of the quantitative video analysis technique as developed for the unobtrusive observation and analysis of road user behaviour is given in Section 3.2. For a more detailed description the reader is referred to Van der Horst [1990]. Section 3.3 discusses several time related measures as applied in the behavioural studies briefly described in Section 3.4.

3.2 VIDeo Analysis of Road Traffic Scenes: VIDARTS

The procedure described here deals with the unobtrusive observation of road users in actual traffic situations by video.

In most of the research, an accurate measurement of trajectories of individual road users in relation to the road environment or to other road users is required as a function of time. From those trajectories (successive positions in time) other variables such as heading angle, velocity, acceleration or time-to-collision can be derived.

Making video recordings of actual traffic is not that complicated in itself. However, the major question is how to extract the relevant data from the huge amount of information available in video images. Of course, a fully automated real time image processing procedure would be highly preferable. Although the developments are rapid, the current state of technology does not enable an approach that is realistic in this sense at this moment. First, a real time analysis can be needed in video monitoring road traffic for traffic surveillance, traffic control, or traffic management. In most of our applications the requirement for real time processing is not urgent; road traffic scenes can be recorded on video tape and analysed off-line frame to frame in the laboratory. Second, in many applications it appears to be effective to make a preselection of relevant events before a detailed quantitative analysis is started. The

complexity of the analysis procedure to be developed can be further reduced by an analysis process with interactive communication between the system and a human operator.

One of the laborious tasks in analysing video tapes is the precise selection and location of the right video frames on the tape. Therefore, an automatic control for positioning a video tape is preferred. To enable a flexible use of the equipment, the implementation of a great part of the system by computer software seems advantageous.

3.2.1 General procedure

In brief, the procedure consists of making video recordings with one or more fixed cameras on the spot and subsequently an off-line quantitative analysis in the laboratory with specially developed video analysis equipment.

The quantitative analysis consists of selecting positions of points on a vehicle by positioning an electronic cursor on a video still. By a transformation based on at least four reference points (see Section 3.2.4) the x- and y-coordinates of the video plane are translated into positions on the road plane. Since movements of more than one road user have to be analysed in relation to each other a road-fixed coordinate system is used. By analysing successive video stills, a sequence of positions over time is obtained, from which other variables such as velocity, acceleration, heading angle, and time-to-collision measures can be derived. Sometimes, a more simple procedure can be applied, viz. measuring time moments of passing given successive road positions instead of measuring positions at successive time intervals. For example, by measuring the moments when two lines with a known distance in between are passed by a vehicle, a simple speed measurement can be taken.

3.2.2 Video recordings

The first step in the data collection consists of making video recordings of traffic scenes at intersections or road sections. A suitable place for mounting the camera has to be found in the neighbourhood of the location, preferably at a height of more than 4 m above the road surface. Of course, a first requirement is that the observations do not influence the behaviour one is interested in. For that reason the placing of a video camera on the roof of a van or on a telescopic mast was rejected. Mostly, a good and unobtrusive camera position can be found either in adjacent buildings, on a balcony, in lampposts or other elements already present at the location.

Basically, the video recording equipment consists of three parts, the camera, a combined synchronisation/timer/field-encoder unit and a video recorder. Until now, black/white video cameras have been used because of their superior horizontal

resolution. When the outlook of the location is too limited or the area is too large to be covered by one camera, additional cameras, video-wipers and/or recorders are optional. It is important that all equipment is correctly synchronised and that each video signal to be separately recorded is coded identically by the timer/field encoder unit. This unit superimposes a numerical display of date and time of day (up to 1/50 s) onto each video image, together with a special digital code at the beginning of the video lines. This 24 bit digital code (one to one related to the time of day) uniquely labels each video field and is used for the automatic computer-controlled search for any given image during the analysis procedure.

Usually, the recordings are made by a Umatic video cassette recorder (speed 50 fields/s) for selected time periods. Optionally time-lapse video recordings can be made for the whole period the camera is running for monitoring purposes and for an efficient counting of traffic flows. When no direct judgements from tapes have to be made by human observers and the frequency of occurrence of relevant events is low, the use of a time-lapse video recorder can considerably reduce the total amount of material. A frequently used reduction factor of 4 (12.5 fields/s) enables the storage of a full 12-hour period on one 3h VHS video cassette.

3.2.3 Video plotting procedure

The basic configuration of the video plotting device is given in Fig. 3.1. An IBM/AT computer forms the central part of the system. One of the laborious tasks in analysing video tapes is the precise positioning of the tape at the right image. The video recorder operates under full computer control. Any given picture can be automatically searched by the computer through the use of the special digital time code that is stored in each video field during the recordings.

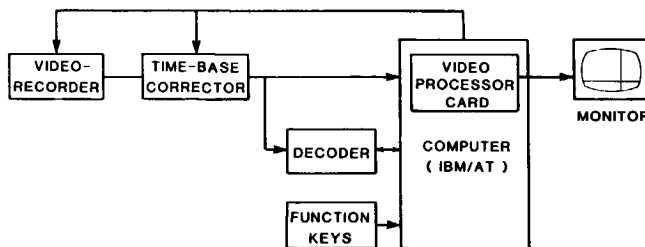


Fig. 3.1 Basic configuration of the video plotting device.

The time-base corrector is used for enhancing the sync part of the video signal before it is processed by the rest of the system. The video processor with frame grabber and a 8 bit 1024x1024 video memory (of which 520x576 pixels are used) enables a flexible

use of the equipment because a lot of features can be implemented in software. For example, for simple speed measurements a programmable electronic grid can be generated; for measuring positions a cursor can be generated which can be manipulated either by computer or human operator control. Also simple image processing procedures, such as an automatic detection of traffic signal changes directly from the video image, can be implemented rather easily in software. A special additional keyboard with 24 programmable function keys enables the operator to communicate with the system rather efficiently. For the first few images of a sequence the operator has to position the cursor on a given point of the vehicle. When a few images have been analysed, an algorithm predicts the expected position of the point based on the x- and y- positions in previous images. Then, the operator has only to indicate small corrections on those estimated positions.

3.2.4 Transformation from video-image to road plane

In earlier studies on the quantitative analysis of film or video recordings, mostly a grid transformation was used for the conversion of image coordinates to road coordinates [Hayward, 1971; Balasha, Hakkert and Livneh, 1978]. However, assuming that 1) all points of the road surface are in one flat plane and 2) no distortion errors from the optics of the camera occur (correct central projection), the method of two-dimensional projective coordination [Hallert, 1960] is much simpler to apply. The transformation of video image coordinates (X_v , Y_v) to road coordinates (X_r , Y_r) is given by a broken linear function of the following form:

$$\left. \begin{aligned} X_r &= \frac{C_1 \cdot X_v + C_2 \cdot Y_v + C_3}{C_7 \cdot X_v + C_8 \cdot Y_v + 1} \\ \text{and} \\ Y_r &= \frac{C_4 \cdot X_v + C_5 \cdot Y_v + C_6}{C_7 \cdot X_v + C_8 \cdot Y_v + 1} \end{aligned} \right\} \quad (1)$$

The coefficients C_1 to C_8 can be calculated if the coordinates of at least four points are known both in the image plane and in the road plane. Substituting the X_r , Y_r , X_v and Y_v coordinates of the four points in Eq. (1) results in a system of eight linear equations with C_1 to C_8 as variables. This system can be solved if no combination of three points in either plane is on a straight line. This method offers the great practical advantage that nothing has to be known about the internal and external orientation of the camera. All information is included in the way the four reference points are projected on the image plane.

It is obvious that the smaller the pitch angle of the camera, the more sensitive to measuring errors the transformation will be. In general, the accuracy will improve when the optical axis of the camera is oriented as vertically as possible (the higher the camera position the better), and the four reference points are maximally spread over the area to be covered. In order to have a check on the transformation and to be able to conduct an optimisation procedure on the transformation (see Appendix A), some additional reference points have to be included. A total number of eight to ten points appears to give reasonable results. In actual road scenes it will almost always be possible to find natural markings that are clearly readable from the video image.

3.2.5 Computation of motion parameters

It is evident that the accuracy of the measurement of positions may be influenced by several factors. A relatively high position of the camera(s), a large pitch angle, a careful selection and accurate measurement of reference points are a first step in reducing errors. An optimisation of the transformation coefficients based on all available reference points, minimises the influence of random errors in the measurement of the reference points. Parallax errors can be avoided by taking the contact point between tire and road surface as the precise point to be measured. By filtering the video coordinates before the transformation to the road plane is conducted, by determining the resulting position from two or three separate points of the vehicle, and by smoothing successive positions by means of a second order polynom filtering, the overall accuracy can be considerably improved; for further details see Van der Horst [1990].

Vehicle velocity is obtained by differentiating successive positions with respect to time, and acceleration found by differentiating successive velocities. For most applications it is not necessary to analyse each individual video frame; a selection of one picture out of every twelve (one picture/0.24 s) appears to be a reasonable compromise between accuracy and duration of plotting.

3.3 Time-related measures

From the trajectories of individual road users, i.e. successive road positions in time (obtained from video scenes) several additional measures can be derived. As discussed in Chapter 2, describing road user behaviour in time measures seems to be advantageous because both velocity and distance can be combined into one variable. In interactions between road users the Time-To-Collision (TTC) measure describes how imminent a collision is. For describing the decision-making process at signalised

intersections the use of the Time-To-Stopline (TTS) instead of the Distance-To-Stopline (DTS) compensates for different approach speeds. TTS indicates how far an individual road user is away from the stopline at the onset of the yellow signal, given his individual speed. A similar time measure can be defined for approaching any given area, for example an intersection. In a study on road user behaviour in approaching non-signalised intersections the Time-To-Intersection (TTI) is used.

In defining these time measures one has to make assumptions about the extrapolation of the vehicle movements from the last observation. Mostly, the extrapolation of movement is based on constant longitudinal speed and heading angle [Hayward, 1972; Van der Horst, 1982]. Balasha et al. [1978] stated that a continuation of movement based on a constant acceleration (or deceleration) and a constant angular velocity would better meet the kinematic process of vehicle movements. This simulates a situation where the driver does not react anymore, viz., the steering wheel and the state of the brake pedal are assumed to be fixed. The assumption of constant acceleration seems to be quite realistic in actual traffic situations. However, both at intersections and road sections a constant angular velocity could easily result in an unrealistic path off the road. So, in what follows the continuation of movement will be either based on the assumption of constancy of speed (TTC) or constancy of acceleration (TTCA), while the heading angle is kept fixed.

Time measures such as TTC can be calculated as long as during the approach process a collision course (one of the vehicles will enter the intersecting area while the other has not left yet) is present. However, specific types of interactions can be considered critical although during the approach, strictly speaking, no collision course is present, and consequently, no TTC can be computed. Mostly, these interactions can be characterised by a very small time gap between the moment of arriving at the intersection area by one of the vehicles and leaving that area by the other. These type of interactions can be met by the Post-Encroachment-Time (PET). TTC and PET will be discussed in some more detail in section 3.3.1 and 3.3.2, respectively. The measures TTS and TTI will not be discussed separately. For each road user who is confronted with the end of the green phase, TTS is defined as the distance to the stopline divided by his individual speed at the onset of the yellow signal. TTI is defined as the distance to the intersection divided by the speed at any given time moment.

3.3.1 The Time-To-Collision concept (TTC)

The Time-To-Collision (TTC) measure is used as (one of) the indicator(s) for the danger or the risk of a collision. In principle, the lower the TTC value during the approach, the higher the risk of a collision will be. Hayward [1971, 1972] defined the

time-measured-to-collision (TMTC or TTC) as the time required for two vehicles to collide if they were to continue their speed and were to remain on the same path. As long as a collision course is present, TTC is a continuous function of time. The general shape of a TTC curve is given in Fig. 3.2. If two vehicles are not on a collision course, the value of TTC is infinite.

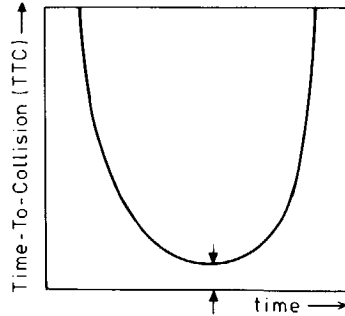


Fig. 3.2 Theoretical TTC curve as a function of time [Hayward, 1972].

A change in speed or path may lead to a collision course, implying that TTC is finite and decreases over time. The function is linear when both speed and heading-angle of the two vehicles remain constant. If none of the vehicles changes its speed and/or course a collision will result ($TTC = 0$). An evasive action (decelerating, swerving) may lead to a minimum value for TTC, TTC_{min} , after which TTC increases to infinity again.

When road users are on a collision course, it rarely results in an actual collision, because drivers continuously make the necessary speed and heading changes. To illustrate TTC, Fig. 3.3 shows what happens when a car approaches a stationary object. The time histories at left represent an evasive action of normal braking; at the right hard braking. Point A indicates TTC when the braking is started, TTC_{br} , representing the available manoeuvring space at the onset of braking. Point B gives TTC_{min} as reached during the approach. Mostly, the concave shape of the TTC curves does not show up so nicely, since in more complex interactions of two moving road users the collision course often is ended before point B. But even then, TTC_{min} indicates how imminent an actual collision has been.

Allen et al. [1977] criticised TTC because it gives infinite values when collisions are avoided even by a fraction of a second, provided no evasive action is taken.

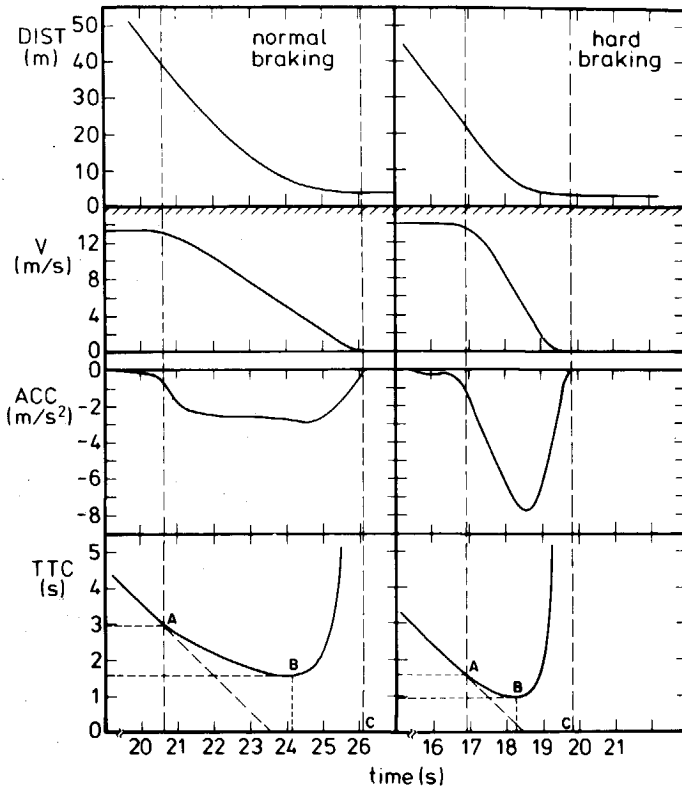


Fig. 3.3 Time histories of normal braking (left) and very hard braking (right) of a car approaching a stationary object; DIST = distance to object, V = velocity, ACC = acceleration, and TTC = Time-To-Collision based on constancy of speed and heading angle. Point A indicates TTC_{br} and point B TTC_{min} .

Glauz and Migletz [1980] also stated that a fundamental issue arises in cross-traffic situations. They describe a left-turn manoeuvre in front of an oncoming car and conclude that in this specific case there is no conflict according to the definition because the vehicles were not actually on a collision course. Van der Horst and Riemersma [1981], however, argued that, first, the assumption that the intersection is taken as a point (for simplicity reasons) may strongly influence the fact whether a collision course is present. The intersection area is defined by the vehicle dimensions and, consequently, the vehicle dimensions determine the collision course (see Appendix B). Second, in the example of Glauz and Migletz there is no collision course at

the moment the manoeuvre is completed. But that does not necessarily imply that there was no collision course during the approach.

In applying TTC at a certain moment t , two basic steps are required:

- a) detecting whether both vehicles are on a collision course (vehicles will meet in the intersecting area), and, if so,
- b) calculating the TTC value at moment t .

Both steps strongly depend on which definition is used for the continuation of movement. Here, TTC will be used for the Time-To-Collision based on a constancy of speed and heading angle and TTCA for the Time-To-Collision based on a constancy of acceleration and heading angle. Appendix B gives details of the calculation of TTC and TTCA.

3.3.2 The Post-Encroachment-Time (PET)

The concept of TTC requires a collision course. However, when road users just miss each other at high speed without considerable path or speed changes there is, strictly speaking, no collision course. Still there is a realistic chance of a collision under such circumstances, i.e. a slight disturbance of the process will easily result in an actual collision. Allen et al. [1977] frequently found this type of encounters for the left-turn manoeuvre at signalised intersections. From an analysis of both collisions and conflicts collected by time-lapse video at one signalised intersection during a fifteen month period, they concluded that the Post-Encroachment-Time (PET) was a promising measure for defining a conflict situation. The PET measure is defined as the time between the moment that the first road user leaves the path of the second and the moment that the second road user reaches the path of the first, see Fig. 3.4.

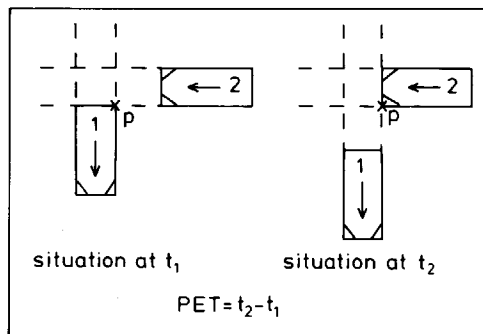


Fig. 3.4 Definition of Post-Encroachment-Time PET.

It gives a measure of how closely a collision was avoided in the final stage of an encounter. Contrary to TTC, the PET measure consists of just one value representing the final time margin that has left between both vehicles. The lower the PET the more likely a collision would have been. PET is comparable with the difference between an accepted gap and the necessary manoeuvring time in gap-acceptance studies [Van der Horst and Ten Broeke, 1984].

3.4 Field observation studies

Several field observation studies form the basis for the analysis of road user behaviour in the next chapters. Because some studies will be referred to in more chapters, a brief description of background and method of each study is given separately in this section. In all studies the behaviour of road users was unobtrusively observed by video and quantitatively analysed according to the procedure described in Section 3.2. The results of these studies will be discussed in Chapter 4 and 5.

3.4.1 Signalised intersections

Background

At signalised intersections the driving task is substantially simplified compared to non-signalised ones. At the guidance level the decision-making process mainly consists of the stopping/non-stopping decision at the moment the signal changes from green to yellow. The greater part of run-red offences appears to be related to this particular moment. From a review of the literature with respect to traffic signal control related measures that could influence this decision behaviour of car drivers, it was concluded that the duration of the yellow phase was of prime importance [Van der Horst and Godthelp, 1982]. An optimum in the yellow timing could be achieved using 4 s of yellow for 50 km/h intersections and 5 s for 80 km/h intersections. Compared with current values in the Netherlands, the duration of the yellow should be extended by one second to appropriately serve the driver in normal driving conditions and to meet his minimal needs in deteriorated circumstances. With this change in yellow timing the number of run-red offences would be considerably reduced, simply because it is expected that by this extension the drivers' behaviour will not change. On the other hand, the yellow timing should not be longer either because first, the stopping driver has to be 'rewarded' with red (confirmation of appropriate behaviour), and second, an overlong yellow time might lead to greater variability in the decision-making, resulting, for example, in an increase of the number of rear-end collisions. Evidence for the latter was found in studies on the safety effects of flashing green [Knoflacher, 1973; Mahalel and Zaidel, 1985].

In a field experiment at both urban and rural locations, a one second extension of the yellow was evaluated under contract with the Transportation and Traffic Engineering Division of the Dutch Ministry of Transport (Rijkswaterstaat, Dienst Verkeerskunde).

Method

Because of current practice in The Netherlands, research on the effects of a change in yellow-timing can be conducted only by means of a before-and-after study in an experimental area with a sufficient number of signalised intersections (drivers have to be used to signalised intersections), and with a relatively small amount of traffic from outside the experimental area. Here only the part dealing with the urban situation will be discussed. The city of Leeuwarden appeared to be appropriate, having 23 signalised intersections in total. All intersections are provided with vehicle-actuated signal control. With all 23 intersections the yellow-time was changed from 3 to 4 s without shortening the all-red time so that possible interfering effects could be prevented. The study was conducted at one approach to each of four selected intersections. At these four locations along with the 'before' measurement a 'one-year after' measurement was carried out. In addition, at two locations a 'six-month after' measurement was made to detect whether or not an adaption of drivers, if any, had reached a final stage.

One measurement consisted of a total of 36 hours of video recordings during four subsequent weekdays. At each location two video cameras were used, one directed on the approach lane and the other on the area near the stop-line and the traffic lights. Both images were fitted into one video signal and, together with time of day and digital label, recorded by a time-lapse VHS video-recorder (see Fig. 3.5). With a reduction factor of four each 0.08 s a video picture was recorded on tape. In doing so the amount of videotape could be reduced substantially without losing any relevant information.

The analysis of the video pictures was conducted by a four-step procedure:

- 1) All traffic light changes are detected automatically by digitising and image-processing the video pictures and storing all the digital labels (in fact, time moments) of signal light changes;
- 2) with the help of the digital labelling system each onset of the yellow signal is selected automatically on video tape;
- 3) a human operator detects whether a vehicle is present in the approach area. If so, he indicates the type of vehicle (car or lorry) and the decision to stop or to proceed. Then he selects seven successive positions of the vehicle by positioning an electronic cursor on the video screen, and for the non-stopping cars he indicates the moment of passing of the stop-line;

- 4) after a transformation of video coordinates to road coordinates, various measures are calculated such as the Distance-To-Stop-line (DTS) and approach speed (V) at the onset of yellow, the Time-to-Stop-line at the onset of yellow (TTS, given by DTS / V), and for the non-stopping cars the Time-of-Passing-Stop-line (TPS) from the beginning of yellow.



Fig. 3.5 Video picture as recorded with two cameras: the upper image includes the traffic light and stop-line; the lower part the area to about 100 m from the stop-line.

For about 15000 traffic signal changes in total 7000 'deciding' vehicles (the non-stopping plus first stopping cars after the onset of yellow) were registered. For more details about this study, see Van der Horst et al. [1985] and Van der Horst and Wilmink [1986].

3.4.2 Railway grade crossings

Background

In The Netherlands about 60% of all collisions between trains and cars occurs at railway grade crossings protected with an automatic signal control and a bell-sound (Dutch abbreviation for this type of railway grade crossing: AKI). Alternating flashing

red lights indicate the approach of a train and road users have to stop and wait, unless they are that close to the tracks that proceeding and clearing the tracks is the only appropriate behaviour. A single flashing white light indicates that no train is coming. Such railway grade crossings appear to be unsafe compared to crossings with automatic half-barriers [Hauer and Persaud, 1987].

Little is known about the causes of accidents at this type of railway grade crossings. Furthermore, road user behaviour prior to accidents is almost impossible to observe systematically. Even observing a statistically sufficient number of drivers running the red light in a late stage would be very time consuming and expensive. Therefore, it was decided to observe approaching drivers both during the red and the white signal phase and to try to extrapolate from observed more frequent behaviour to possible accident causes. This observational study was supported by the Road Safety Directorate of the Dutch Ministry of Transport.

Method

For this study two railway grade crossings with automatic signal control were selected with a straight approach perpendicular to the tracks, good visible lights, and relatively high traffic volumes for both cars and trains (50 to 150 veh/h and 6 to 12 red phases/h).

At each of the two crossings approaching cars were videotaped for ten hours a day on seven subsequent working-days. Two video-cameras were mounted in lampposts, one for registering the approach from about 70 m before the tracks and the other for having a close look on the lights and the area close to the tracks. The images from both cameras were combined into one video signal and recorded on a time-lapse VHS video-recorder at 12.5 fields/s. During the last two days also Umatic video recordings at normal speed (50 fields/s) were made from a third camera mounted behind a fence at drivers' eye height for assessing head movements over the last 24 m of the approach.

The behaviour of car drivers during both the red and the white signal indication was analysed. During about 1260 red phases a total 660 motorists had to make the decision to stop or to proceed (all non-stopping and first stopping cars after the onset of the red signal). Of each red phase the following characteristics were registered from video using the video plotting device as described earlier:

- the moment of onset of the red phase,
- the moment of arrival of the first train,
- the moment the crossing was cleared by the first train,
- the moment of arrival of a second train, if applicable,
- the moment the crossing was cleared by the second train, if applicable, and
- the duration of the red phase.

Of each 'deciding' car the following characteristics were derived:

- position at the onset of the red signal,
- speed at the onset of red (based on seven position samples over time),
- the action taken: stop or cross, and
- moment of passing the first track.

Because drivers did not appear to refer their place of stopping to the stop-line, the first track was taken as a reference for calculating TTS, the remaining time before crossing at the onset of the red signal, according to:

$$TTS = DTS / V \quad (2)$$

with DTS = distance to the first track at the onset of the red signal (m),

V = initial speed (m/s).

Of a total of 272 free riding cars (136 at each AKI) approaching during the white flashing light period, the position was measured every fourth field (0.24 s) until the front wheels crossed the tracks. Free riding is defined as approaching and crossing without oncoming traffic present and no leading vehicle within 5 s. Similar to Eq. (2) an instantaneous time to the first track (TTI) can be calculated based on the distance to the first track and the speed V at any given moment, allowing a description in time of the whole approach. For more details about this study the reader is referred to Tenkink et al. [1987] and Tenkink and Van der Horst [1988].

3.4.3 Non-signalised intersections

Background

In the literature little is said about the effects of priority rules and regulations on road user behaviour [Janssen and Van der Horst, 1988]. Although knowledge on priority rules itself is rather limited [Helmers and Aberg, 1978], road users appear to manage the majority of encounters without problems. The way they do this doesn't necessarily reflect the formal juridical rules. In the Netherlands the general right-hand right-of-way applies at intersections without specific regulation. However, there is one exception on this general rule: a bicyclist or moped rider has to yield to motor vehicles on the intersecting road. Because in all neighbour countries this exception is not made, one was considering to repeal this exception rule. Under contract with the Transportation and Traffic Engineering Division of the Dutch Ministry of Transport an explorative study was conducted to identify and describe the behavioural rules as applied by road users in a priority situation.

Method

Behaviour was observed by video registration at two locations, one having a special priority regulation (indicated by yield signs and pavement markings), the other without specific regulation (so that the general regime of right-hand right-of-way with the exception for bicyclists applied). The selection of both locations was such that both had a comparable standard geometry with a distinguishable major and minor road, but without separate bicycle lanes or parallel roads. Also the visibility conditions (reasonable) and traffic volumes (about 300 veh/h and 30 bicycles/h on the major road and about 100 veh/h on the minor road) were comparable for both intersections.

At each intersection video recordings with three cameras were made during three working days (8.00-18.00 h). Two cameras were at a high position in an adjacent apartment building, one covering the approach area of the major road and the other that of the minor road with the intersecting area partly in common. A third camera was at street level, unobtrusively mounted in the back of a parked car and registering head movements of road users at one of the approaches.

Encounters were selected from video with a criterion of a PET less than 5 s and no more than two road users involved in the interaction. Only encounters between a car from the minor road and a straight-on going or left turning car or bicycle on the major road were considered. For the observation period in total 644 encounters were selected. In order to separate behaviour in an interaction from that conducted to negotiate the intersection per se, a total number of 171 free-moving cars from the minor road without traffic on the major road was also selected for further analysis.

The analysis of the selected video scenes consisted of three parts:

- 1) Determining the final outcome of an encounter in terms of who was going first;
- 2) Computation of positions and speeds of the vehicles involved as a function of the running time, also resulting in the computation of the Time-To-Intersection (TTI) measure;
- 3) Registration of the moments of head movements of one of the road users to the left and to the right. Sequences of head movements were used as an indicator of where attention was directed to.

For more details about this study the reader is referred to Janssen and Van der Horst [1988] and Janssen et al. [1988].

3.4.4 Bicycle route intersections

Background

In the Netherlands, with about 11 million bicycles and 5 million passenger cars, bicyclists and moped riders form a vulnerable group of road users. In 1984, 30% of the people killed in traffic consisted of bicyclists and moped riders. Among others because of environmental reasons, the Dutch government's policy aims at a restricted car use, especially in urban areas during rush hours, and to promote the use of the bicycle and/or public transport instead. To stimulate the construction of safe and highly comfortable bicycle routes in urban areas, the central government designed and constructed two demonstration bicycle routes at The Hague and Tilburg. At all non-signalised intersections the bicyclists have the right-of-way over crossing traffic. At these intersections several new geometric design elements were applied for supporting the intended road user behaviour, such as speed control humps, different asphalt colour of bicycle route pavement, lane narrowings, cobble pavement, etc.

Under contract with the Transportation and Traffic Engineering Division of the Dutch Ministry of Transport a field study was conducted to evaluate the functioning of these special road design elements at the priority intersections in terms of road user behaviour.

Method

Because in most cases both the lay-out of the intersections and the traffic patterns were considerably changed, a before-and-after study design was not suitable. However, the experimental character of the demonstration project made it possible to implement some solutions for the same kind of problems at different intersections having comparable characteristics. The evaluation consisted, among other things, of a comparison between:

- the actual behaviour at the experimental locations and the behaviour as intended by the designers;
- the actual behaviour at different experimental locations;
- the actual behaviour at experimental locations and the behaviour at control locations without special provisions.

At fifteen locations of the bicycle routes (ten at The Hague and five at Tilburg) and at five separate control locations, video recordings were made, at each location for six hours during one day. The video recorder was started by hand when a vehicle from the minor road arrived and stopped when the manoeuvre was over. For practical reasons a preselection of relevant interactions between bicyclists on the cycle route and crossing traffic was made before a quantitative analysis was conducted.

Only those encounters were selected for which it was estimated from video that an actual collision course was present and the proximity in time was rather close (estimated TTC_{min} less than 2.5 s). Moreover, encounters without an obvious collision course but with a low PET value (less than about 1 s) were selected for a quantitative analysis. In total more than 2,000 interactions between bicyclists on the cycle routes and crossing traffic were quantitatively analysed. At several intersections also the approaches of a number of free riding cars (all together about 950) were analysed.

Figs. 3.6 through 3.10 give the lay-outs of the intersections that will be separately discussed in the next chapters. A description of the other locations and more details on the project are given in Van der Horst [1980, 1984a].

Fig. 3.6 Experimental location H1 at The Hague with a bicycle track with two-way bicycle traffic at one side of the main road and speed control humps at a distance of about 5 m to the cycle track.

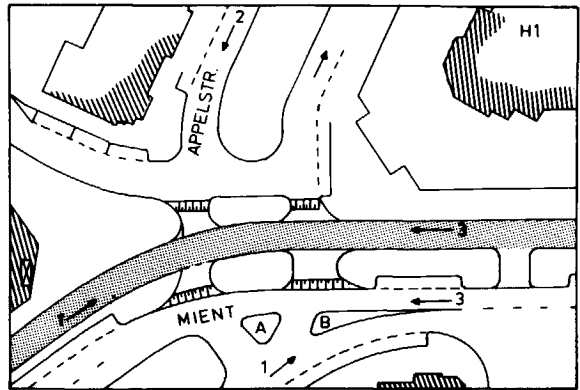
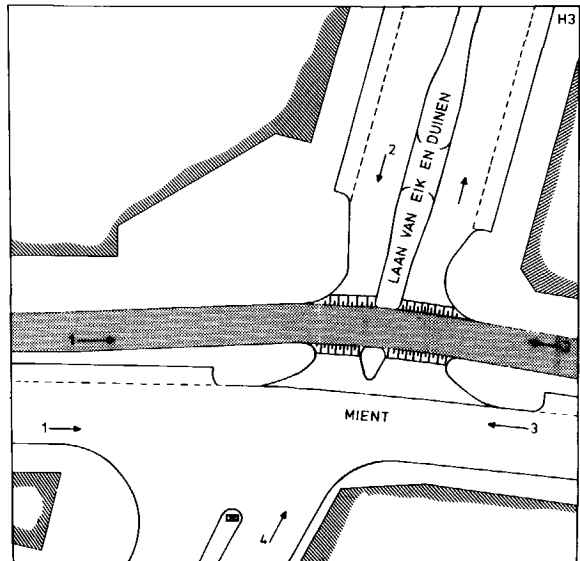


Fig. 3.7 Experimental location H3 at The Hague with a bicycle track with two-way bicycle traffic at one side of the main road and speed control humps bordering the cycle track.








-  bicycle track
-  speed control hump

Fig. 3.8 Experimental location T1 at Tilburg consisting of a mid-block bicycle route road crossing. One approach direction of crossing traffic (from direction 4) has a short median (11 m), the other (direction 2) has a long median (50 m).

-  bicycle track
-  speed control hump
-  cobble pavement

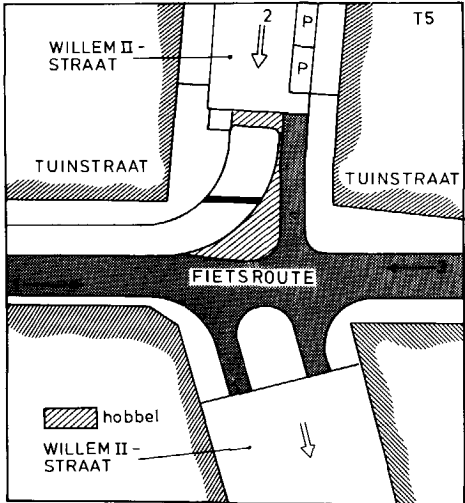
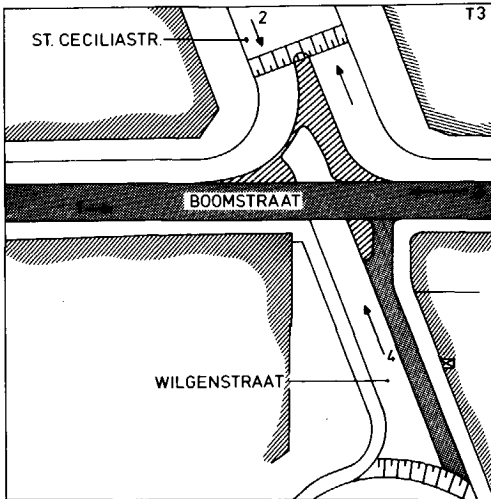
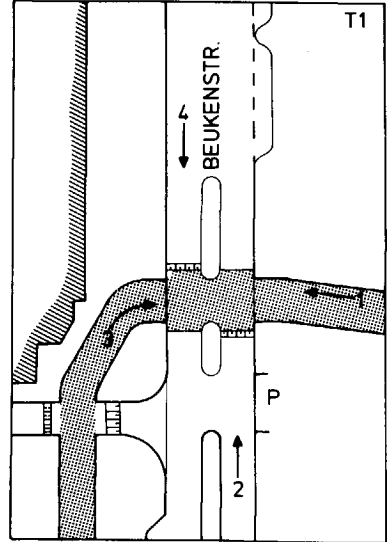


Fig. 3.9 Experimental location T3 at Tilburg with two speed control humps of moderate height at about 10 m and 5 m to the cycle track, and a yield priority regulation. Only straight-on going car traffic from direction 2 intersects with the cycle track. Car drivers have a reasonable view close to the track.

Fig. 3.10 Experimental location T5 at Tilburg with a high triangular speed control hump of cobble pavement and a stop sign regulation (only straight-on car traffic from direction 2 intersects). At the stop-line the view on the track is poor.

3.4.5 The Malmö calibration study

Background

Since the systematic observations of traffic conflicts by Perkins and Harris [1967], traffic conflicts techniques have been developed in many countries. Differences in local circumstances resulted in a variety of definitions, observation methods, severity scores, etc. Co-operation by the International Committee on Traffic Conflicts Techniques (ICTCT) resulted after three workshops [Oslo, 1977; Paris, 1979; Leidschendam, 1982] in a joint international calibration study. The primary aim of this study was to investigate the similarities and differences among the various techniques when applied in combination in one field study with sufficient variation with regard to location, type of manoeuvre, road users involved, etc. A more long-term objective was to determine whether results obtained by one technique could be used by others.

Teams from ten countries participated: Austria, Canada, Denmark, Finland, France, Germany, Great Britain, Sweden, The Netherlands, and the United States. Participation in this study gave the unique opportunity to relate the results from an objective quantification of interactions between road users based on video, to techniques using human observers in the field. The quantitative analysis was sponsored by the Institute for Road Safety Research SWOV.

Method

All teams simultaneously made observations of traffic situations at three intersections at Malmö, Sweden, in June 1983. Two intersections are located in the city centre of Malmö, one signalised intersection (Fig. 3.11) and one non-signalised low-speed intersection with a general right-hand priority rule (Fig. 3.12). The third one is a non-signalised high-speed priority intersection (yield signs) located near the city centre (Fig. 3.13). The traffic at each intersection was observed by eight observer teams for about sixteen hours spread over three working days, while simultaneous video recordings were made unobtrusively from adjacent buildings. In total 974 traffic conflicts were scored by at least one of the teams. For practical and financial reasons only a subset of these interactions could be quantitatively analysed. Assuming that the more serious conflicts would be scored by more teams, a manageable subset was obtained of those conflicts, that had been scored by four or more teams, e.g. 111 situations. To this set six conflicts were added, namely those that were scored with a very high severity rate by one or more teams.

More details about the locations, the observation procedures, the video analysis procedure and the like, can be found in Grayson (ed.) [1984] and Van der Horst [1984b].

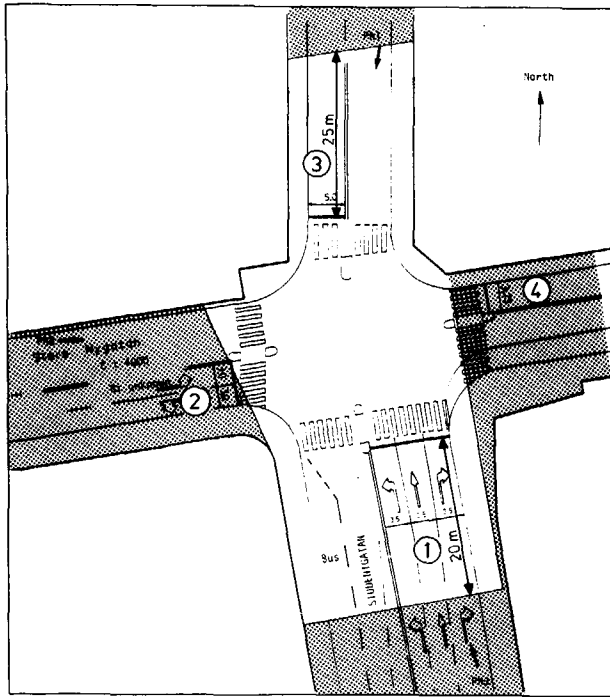


Fig. 3.11 Signalised intersection at the city centre of Malmö with two-phase signal control during off-peak hours. During the afternoon peak hour there is an exclusive left turn phase at approach 1.

Later on it was decided to analyse one day of observation in more detail, i.e. to get additional information from the conflicts that had been scored by less than four teams, and to check whether conflicts had been missed by all observer teams in the field. For this analysis the first day of observation at the general rule intersection was selected (day 7). Firstly, all conflicts that had been scored by at least one of the teams during that day (122 conflicts in total) were analysed quantitatively. Secondly, a careful inspection of the video tapes was conducted to select encounters with a close proximity of the road users involved, and that possibly had a minimum TTC of less than 1.5 s but not had been scored by one of the teams in the field. This resulted in a quantitative analysis of another 100 situations.

Fig. 3.12 Non-signalised low-speed intersection with a general right-hand priority rule at the city centre of Malmö.

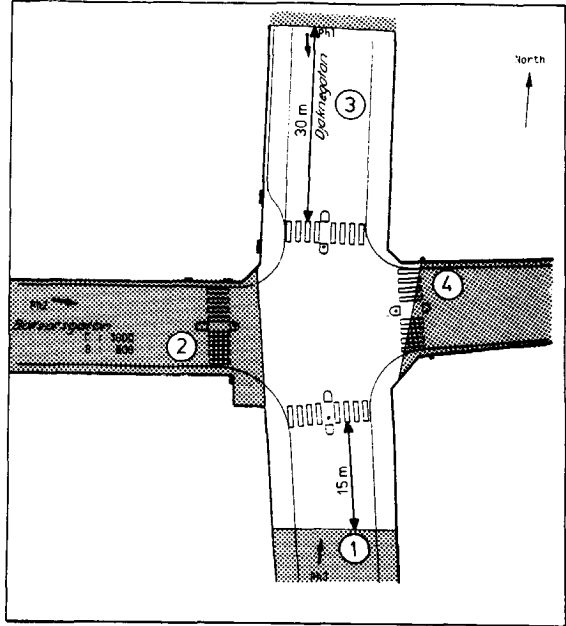
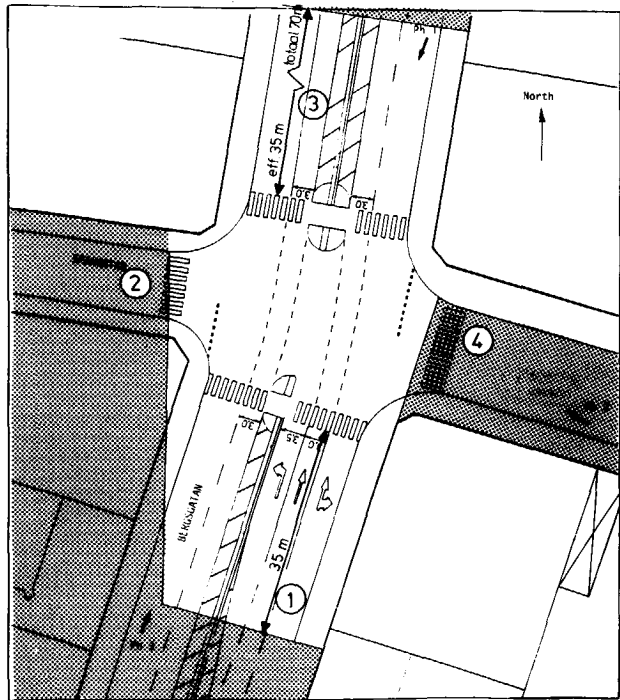


Fig. 3.13 Non-signalised high-speed priority intersection (yield sign regulation) near the city centre of Malmö.



3.4.6 The Trautenfels calibration study

Background

The Malmö calibration study dealt only with intersections in urban areas. A joint road safety study by the Bundesanstalt für Strassenwesen (BASt), West-Germany, and the Kuratorium für Verkehrssicherheit (KfV), Austria, on some transit tourist routes through Austria, enabled the ICTCT to supplement the Malmö study with a calibration of Traffic Conflicts Techniques at an intersection in a rural area. For this purpose the junction of two major international routes through Austria near the village of Trautenfels was selected. Traffic conflict observation teams from six countries participated: Austria, Finland, France, Sweden, The Netherlands and the United States. An Israeli team examined some aspects separately. The quantitative analysis of the video recordings that were made simultaneously with the field observations, was sponsored by the Transportation and Traffic Engineering Division of the Dutch Ministry of Transport.

Method

The six participating teams observed the traffic at the Trautenfels intersection for 26 hours during four days. Simultaneous video recordings were made from two cameras that were unobtrusively mounted on the top of a lamppost and an overhead sign post of a nearby gas station.

The Trautenfels intersection has a typical lay-out, the central part of the intersection is signalised with a two-phase fixed-time traffic control system, and three of the four right-turning traffic flows use separate right-turn lanes without signalisation, see Fig. 3.14.

Traffic on lane r1 has to yield at point A, at lane r2 the general rule of right-hand priority holds at the merging area B, and the third one (r3) has a stop sign at point C. So, all the possible right-of-way situations are present at this intersection. However, the whole intersection area was too vast to be observed by the limited number of observers of two for each team or to be covered by two video cameras. Therefore, it was decided to concentrate both the observations and the video recordings on the inner area of the intersection (area K with the direct access lanes, see Fig. 3.14) together with one full approach on the major road (approach 3) and one right-turn lane with merging area (r2 and area B with the general priority rule).

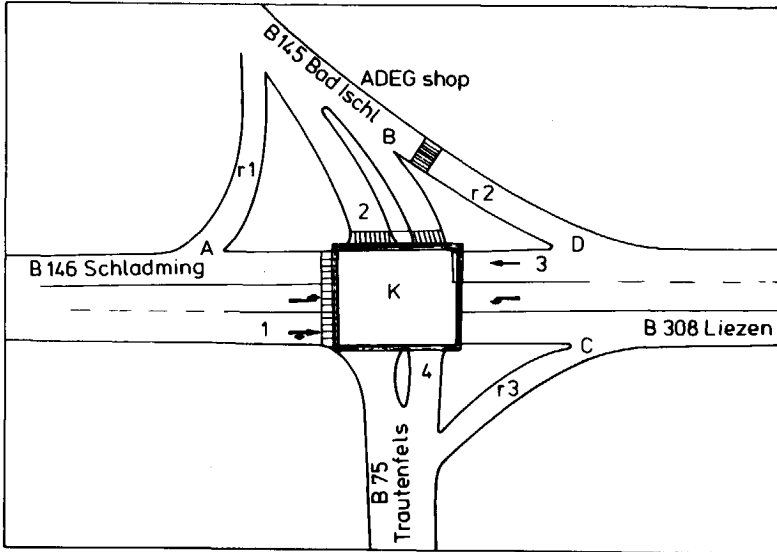


Fig. 3.14 Signalled rural intersection at Trautenfels.

In total, 167 conflicts were registered by at least one of the six observer teams, mainly consisting of car-car interactions. From this total set a number of 45 conflicts could not be quantitatively analysed from video since those situations either occurred at an area of the intersection where the resolution was too low to do so, or were partly occluded by oncoming lorries. Therefore, a set of 122 conflicts is available for further analysis. More details on this study can be found in Van der Horst and Kraay [1985], and in Risser and Tamme [1987].

4 BEHAVIOUR IN RELATION WITH THE ENVIRONMENT

4.1 Introduction

As discussed in Chapter 2 the guidance level of the driving task refers to tasks dealing with the interactions with both the road environment and other road users. To be able to make a clear distinction between the influence of environmental factors and of the presence of other road users within that environment on road user behaviour, both aspects will be discussed separately. In this chapter the emphasis will be on a detailed analysis of road user behaviour in relationship with the environment without the direct presence of other road users. Chapter 5 will deal with the behaviour in encounters with other road users. In the following sections the interaction between road user and environment will be discussed on the basis of two examples, viz. drivers' decision-making at both signalised road intersections (Section 4.2) and railway grade crossings (Section 4.3), and drivers' approaching behaviour at several non-signalised intersections in situations where no other traffic is directly involved (Section 4.4). An attempt will be made to relate drivers' behaviour directly to environmental elements such as traffic signals at signalised intersections and traffic signs and intersection lay-out at non-signalised intersections in terms of time measures.

4.2 Decision-making at signalised road intersections

As indicated in Section 3.4.1 a one second extension of the yellow was evaluated in a before-and-after study at both urban and rural intersections. One year after the yellow extension the last measurement was conducted.

Number of red-runners

From Table I it can be concluded that one year after the yellow timing was changed, the number of red-runners at least has been halved at both the urban and rural intersections. The 'six-months-after' measurements at two urban locations showed a similar reduction.

Table I Number of red-runners (RR) in 'before' and 'one-year-after' period in absolute figures, as well as in percentages of both the total number of vehicles (%TOT), and the number of 'deciding' vehicles (non-stopping and first-stopping cars after the onset of yellow) (%DEC) for the urban (yellow from 3 to 4 s) and rural (yellow from 4 to 5 s) situation.

	RR		%TOT		%DEC	
	before	after	before	after	before	after
Urban	339	172	1.1	0.5	13.4	6.7
Rural	129	46	0.6	0.2	7.4	3.5

Distribution of non-stopping cars

The proportion of non-stopping automobiles with a Time-of-Passing-the Stop-line (TPS) greater or equal to a given time t after the onset of yellow (Fig. 4.1) shows a small shift between 'before' and 'one-year-after' period of 0.13 s for the urban intersections ($D_{\max} = 6.0\%$, Kolmogorov-Smirnov test, one-tailed, $p < 0.01$).

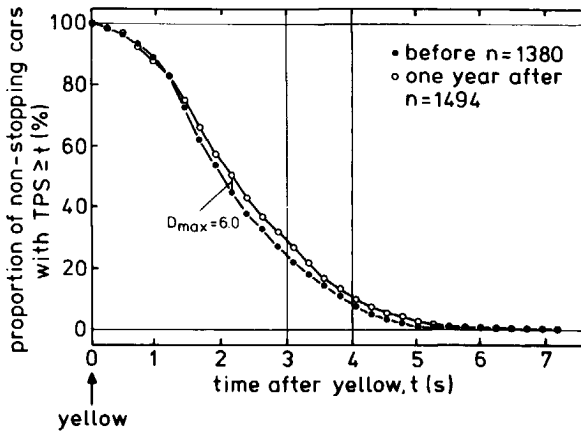


Fig. 4.1 Proportion of the non-stopping cars with a $TPS \geq t$ after the onset of yellow, for 'before' and 'one-year' after the extension of yellow from 3 to 4 s at urban intersections.

Results for the 'six-months-after' period differ by the same amount from the 'before' period, but the 'six-months-after' period does not differ significantly from the 'one-year-after' period. At rural intersections no significant difference in the distribution of non-stopping cars was found between the 'before' and 'one-year-after' period.

Probability of stopping as a function of the Distance-To-Stop-line (DTS)

By including the information from the stopping drivers, the probability of stopping can be defined as a function of, for example, the Distance-To-Stop-line (DTS). DTS is the distance to the stop-line where the car driver is at the onset of yellow. The probability of stopping is defined as the proportion of stoppers divided by the total number of vehicles for each distance-class (class-width of 5 m). Fig. 4.2a gives the probability of stopping for the 'before' and 'one-year-after' period for all four urban intersections together.

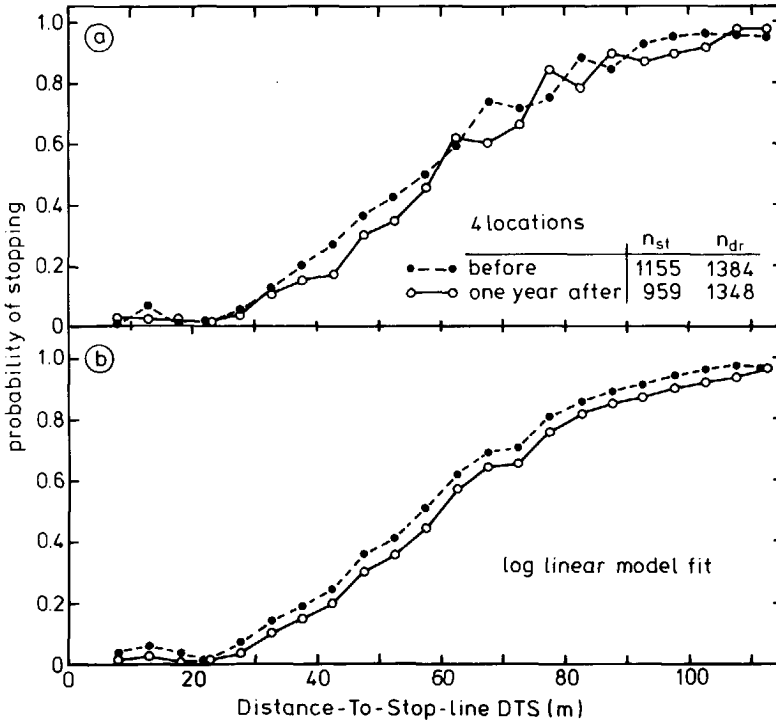


Fig. 4.2 Probability of stopping at urban intersections as a function of DTS at the onset of yellow; a) original data 'before' and 'one-year-after' (n_{st} = number of stoppers, n_{dr} = number of non-stopping cars), b) fit by means of log linear model.

Because, in principle, all observations are independent, a log-linear model analysis is used to test the difference between both curves [Oppe, 1980]. Such an analysis tries to find the simplest model for describing the data adequately together with a good understanding of the amount of dependency between the underlying factors. A small difference between 'before' and 'after' can be distinguished (Fig. 4.2b). The probabil-

ity of stopping curve is shifted about 2.5 m. A similar shift was found for the rural intersections.

Probability of stopping as a function of the Time-To-Stop-line (TTS)

Because it might be expected that the decision of individual drivers not only depends on DTS, but also on their individual approach speed, the probability of stopping as a function of the Time-To-Stop-line (TTS) seems to be a better description of drivers' decision-making. Besides, TTS enables a direct comparison with the yellow time. TTS is the time it will take to reach the stop-line after the onset of yellow assuming that vehicles will continue at a constant speed. Fig. 4.3 gives the results after a log linear model fit. A small shift of 0.17 s is present.

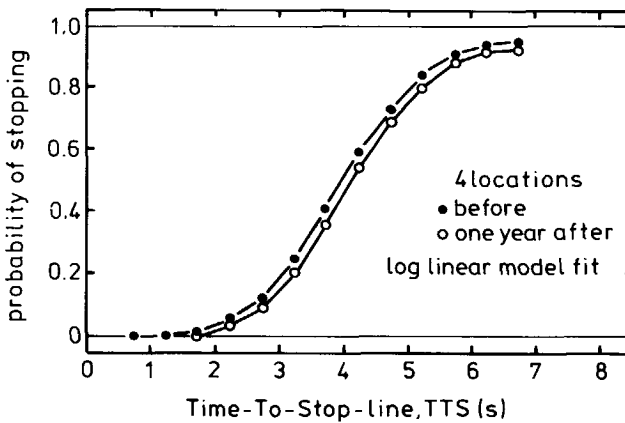


Fig. 4.3 Probability of stopping as a function of TTS at the onset of yellow after a log linear model fit.

The curves don't fully reach the value of 1.0 because of a small artefact in the video analysis procedure. In order to reduce the amount of work, stopping cars more than 100 m away from the stop-line were not measured, while proceeding cars in that area were included. A probability of stopping of 0.5 is reached at TTS = 4 s. A probability of stopping between 0.2 and 0.8 is reached within a range between 3 and 5 s for TTS and within a range between 40 and 80 m for DTS.

At rural intersections no individual speeds have been measured, therefore, for those intersections no TTS could be calculated.

Type of traffic signal control

It might be expected that different types of traffic signal control will differ in terms of exposure to potential offences and will also perhaps differ in the process used by the

drivers to decide whether to stop or to proceed. If a vehicle-actuated control is used, the green phase, in principle, will be extended as long as there are vehicles in a given detection area. When this control strategy operates well, it will result in much fewer potential red runners than does fixed-time cycle control, in which the times selected for ending the green are independent of the instantaneous traffic. Zegeer and Deen [1978] found a large reduction in the number of run red offences when a green extension system was applied. Regardless of the duration of the yellow, the expectations of automobile drivers might differ for different types of control, resulting in different decision behaviour.

In the study on the yellow timing all traffic signal controls were vehicle-actuated. In Fig. 4.4 the probability function for stopping at vehicle-actuated controlled intersections [Van der Horst and Wilmlink, 1986; Sheffi and Mahmassani, 1981] is compared with data on fixed-time control [Mahalel et al., 1985; Williams, 1977; Hulscher, 1984].

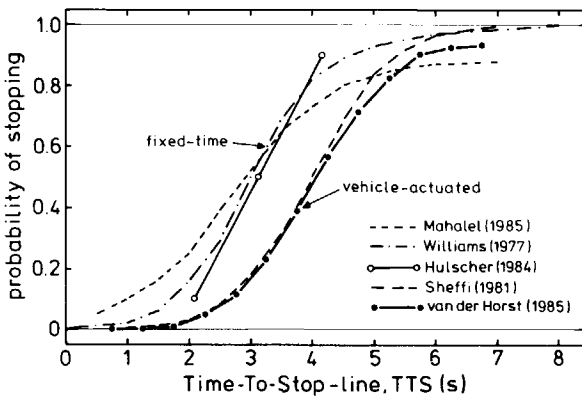


Fig. 4.4 Probability of stopping as a function of TTS for fixed-time versus vehicle-actuated signal control.

All data sets are based on field studies, except the one from Mahalel et al. [1985]. They conducted a laboratory experiment on the decision-making behaviour of car drivers at traffic lights. A remarkable one-second shift exists between the probability of stopping for a fixed-time control and that of stopping for a vehicle-actuated control. In the field studies, it was observed that the characteristics of the decision process itself are not different, as is indicated by the similarity of the slopes of the curves at a 0.5 probability of stopping. The slope of the laboratory experiment at this point tends to be different, indicating a somewhat deviant behaviour in more artificial circumstances.

4.3 Decision-making at AKI railway grade crossings

At two AKI railway grade crossings the behaviour of approaching car drivers was observed, both during the red and the white signal phase (see Section 3.4.2). In Section 4.3.1 the decision-making of drivers at the onset of the red signal will be discussed and compared with that at signalised road intersections. Section 4.3.2 deals with the behaviour of drivers approaching the railway grade crossings during the flashing white signal.

4.3.1 Behaviour at the onset of the red signal

Distribution of non-stopping cars

At AKI's the proportion of non-stopping cars with a TPS greater or equal to a given time t after the onset of the red signal (Fig. 4.5) is significantly lower than at signalised intersections with vehicle-actuated control at the onset of the yellow ($D_{\max} = 24.3\%$, Kolmogorov-Smirnov test, two-tailed, $p < 0.001$). No drivers were observed to cross later than 6 s after the onset of the red, in spite of a margin of over 16 s until a train could arrive. Running the red lights almost exclusively occurs in the early red phase where drivers are simply not able to stop.

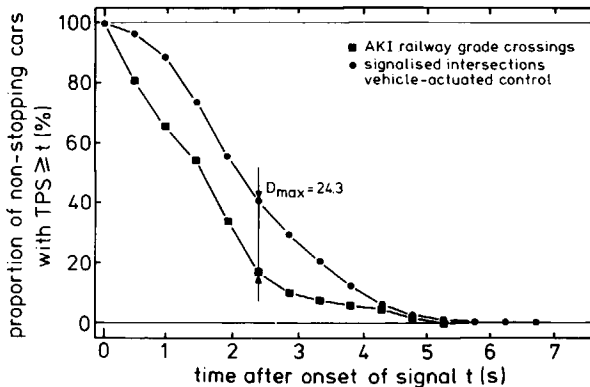


Fig. 4.5 Proportion of non-stopping cars with a $TPS \geq t$ after the onset of signal at AKI railway grade crossings (flashing red) and at signalised road intersections with vehicle-actuated control (yellow).

Probability of stopping as a function of TTS

For a proper description of drivers decision-making also the information from stopping drivers has to be included. For signalised road intersections the probability

of stopping was given as a function of the Time-To-Stop-line (TTS), taking into account both the distance to the stop-line and each individual approach speed at the onset of yellow (Section 4.2). Because at railway grade crossings drivers didn't refer their place of stopping to the stop-line as present at both AKIs, the maximum available time, i.e. the time to the first railway track, was taken as TTS for comparison. Fig. 4.6 gives the results of a log linear model fit of the probability of stopping at AKI crossings and signalised road intersections with vehicle-actuated control ($\chi^2 = 12.06$, $df = 17$).

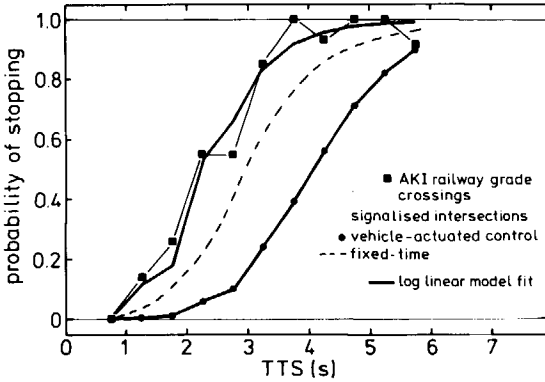


Fig. 4.6 Probability of stopping for AKI railway crossings versus vehicle-actuated controlled intersections after a log linear model fit, together with the probability of stopping for fixed-time controlled intersections [Williams, 1977].

Given a certain TTS at the onset of the signal, the probability of stopping at AKI crossings is much greater, a shift of about 2 s exists between both curves. Unfortunately, no raw data of fixed-time controlled road intersections were available. But also compared with the reported probability-of-stopping curve by Williams [1977] for fixed-time control intersections (see Fig. 4.4), the willingness to stop at AKI crossings is considerably greater than at signalised road intersections.

Probability of stopping as a function of required deceleration

The greater willingness to stop at AKI railway grade crossings is also illustrated by Fig. 4.7a, that gives the probability of stopping as a function of the minimally required deceleration at the onset of the signal to come to a stop just in front of the first track or the stop-line at AKI crossings and vehicle-actuated controlled road intersections, respectively.

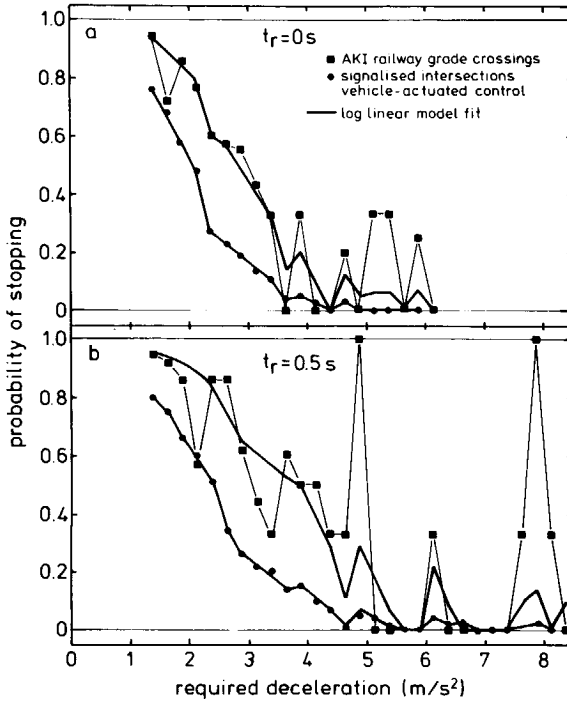


Fig. 4.7 Probability of stopping as a function of the minimally required deceleration rate for AKI railway crossings versus signalised intersections after a log linear model fit, when no reaction time (t_r) (Fig. 4.7a) or a t_r of 0.5 s (Fig. 4.7b) is taken into account.

No reaction-time is taken into account. Again, a log linear model is fitted ($\chi^2 = 17.19$, $df = 18$). At AKI crossings a probability of stopping of 0.5 is reached at a required deceleration of about 3 m/s^2 , whereas at signalised intersections this is at about 2 m/s^2 . Four decisions to stop were made while a minimum deceleration rate of over 4 m/s^2 was needed. Taking into account a (relatively low) reaction time of 0.5 s would already result in a probability of stopping of 0.5 at a required deceleration of about 4 m/s^2 at AKI crossings (see Fig. 4.7b). Then, eleven stops could only be realised with a high deceleration rate of well over 4 m/s^2 . Such breaking has the character of an "emergency" action and can easily lead to a stop just in front of or on the track itself. Indeed, six drivers backed up somewhat after they had come to a halt very close to the track.

4.3.2 Behaviour during the flashing white signal

At AKI railway grade crossings a white light is flashing when no train is approaching. Therefore, the flashing white light informs drivers that they can cross safely. By measuring the behaviour of free riding cars the interaction between driver and AKI crossing was analysed. Free riding is defined as approaching and crossing during the flashing white period without oncoming traffic and no leading vehicle within 5 s. Drivers' uncertainty or lack of understanding of the signal might show up in a slowing down or even an erroneous stop. Erroneous stops appear to be rare, viz. only one in our sample of 272 cars. Deceleration may also be induced by bumps in the road and lane narrowings, usually accompanying railway crossings. That such deceleration occurs, is apparent from the average speed profiles at both AKI crossings, see Fig. 4.8.

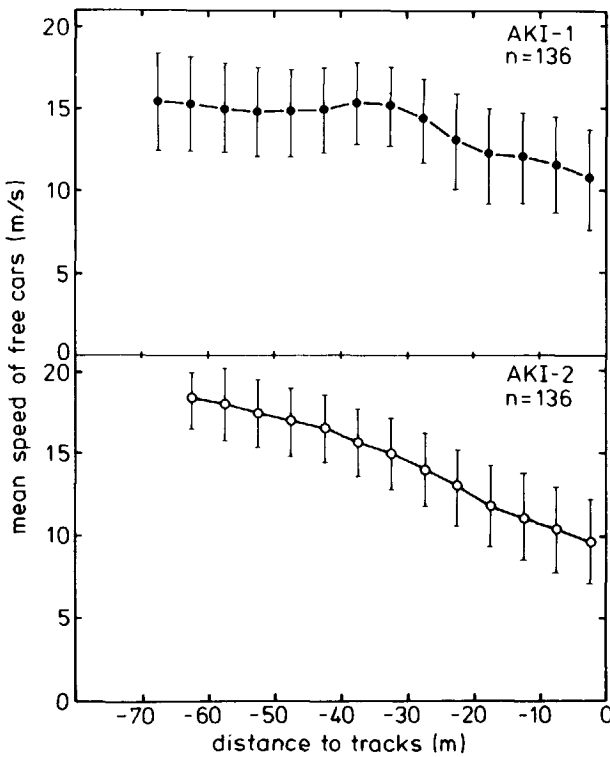


Fig. 4.8 Average speed profile of free riding cars at both AKI crossings. Bars give the standard deviation across drivers.

Then, it is difficult to set a simple criterion such as a given level of deceleration. However, with TTI an objective measure of uncertainty can be derived. This is illustrated in Fig. 4.9 where TTI (defined as the distance to the first track divided by

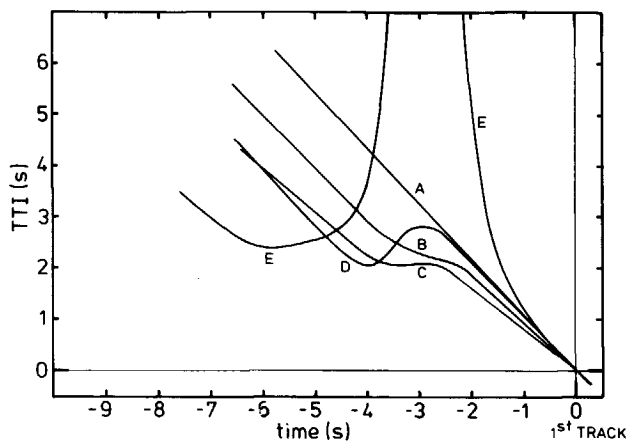


Fig. 4.9 Hypothetical TTI curves for approaching cars as a function of the running time.

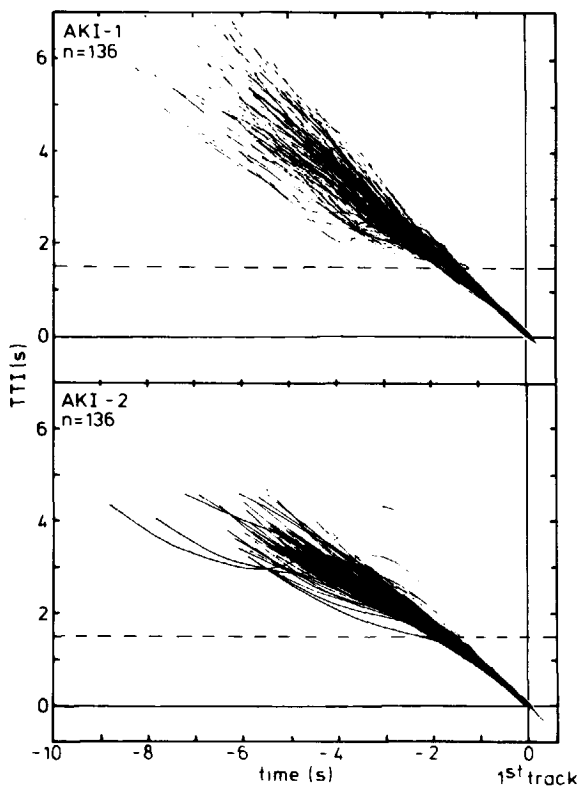


Fig. 4.10 Individual TTI curves of all approaches of free riding cars at both AKI crossings.

the instantaneous speed) is given as a function of the running time for five hypothetical but realistic types of approaches. For each approach the moment of reaching the first track is taken as $t = 0$ s. Curve A illustrates an approach with a constant speed; TTI decreases linearly with time. By decelerating differentially it is possible to reduce the decrease of TTI (curve B), to keep TTI constant for a while (curve C) or even to increase TTI (curve D). A complete stop would result in curve E. Behaviour such as that from curve C or D makes it possible to gain time for interpreting the situation before actually entering the tracks. At AKI-1 and AKI-2 10 and 2% of all approaches, respectively, were characterised by such behaviour. Interestingly, neither TTI at the first minimum or the TTI at the last knee point before entering the tracks exceeds a value of 1.5 s, see Fig. 4.10.

Head movements are a second indication of uncertainty. When only relying on ones own judgement, the minimal requirement for a safe passage would be to make head movements in both directions at least once. From the free riding drivers 18 and 24%, respectively, exhibits this behaviour (Table II); 2 to 6% looks more than once in both directions and 76 to 82% of all drivers apparently knows the correct meaning of the white flashing signal and feels confident to cross without making sufficient head movements.

Table II Percentages of passages without and with head movements at both AKI crossings.

	none	head movements		total	
		one direction	both directions once frequent		
AKI-1	51	31	16	2	100 (n=116)
AKI-2	39	37	18	6	100 (n=131)

4.4 Approach strategies at non-signalised intersections

In order to relate road user behaviour to environmental elements the data of two studies were used to analyse the behaviour of drivers approaching an intersection when no other traffic was directly involved (free-moving cars). A distinction is made between non-signalised intersections without and with separate bicycle tracks. The approaching behaviour as influenced by the type of priority regulation was compared

at intersections without separate bicycle tracks, viz. at one yield intersection and at one intersection with the general right-hand right-of-way rule (Section 4.4.1). At intersections with separate bicycle tracks along the main road the behaviour of free-moving cars approaching from and towards the minor road was analysed to compare the functioning of different intersection lay-outs and road design elements (Section 4.4.2), whereas in Section 4.4.3 the behaviour of free-moving cars only crossing a bicycle track was analysed to evaluate some intersection lay-outs.

4.4.1 Yield vs. general rule intersection

Section 3.4.3 briefly described the study that was used to compare the approach by free-moving cars from the minor road of a yield intersection and an intersection with the general right-hand right-of-way rule. A number of 171 approaches was available, subdivided by type of manoeuvre according to Table III.

Table III Number of approaches by free-moving cars from the minor road by type of manoeuvre and type of intersection.

	left turn	straight on	right turn	total
yield	23	30	30	83
general rule	30	30	28	88

Fig. 4.11 gives the average speed profiles of free-moving cars at both intersections by type of manoeuvre. An analysis of variance (ANOVA) of the speed curves in the area with data for both types of priority regulation (from -18 to 0 m) with dimensions type of priority regulation (P), type of manoeuvre (M), and distance to the main road (D) reveals that all main effects and all interaction effects are significant at a level of $p < 0.0001$. The main effect of D accounts for 26.8% of the total variance, M for 9.4% and P for 3.0%, while the first order interaction P x D explains 5.0% of the variance, P x M 4.1% and M x D 1.1%. The highest order interaction P x M x D explains 1.1% of the total variance. So, both the shape and the position of the speed curves appears to be dependent on type of priority regulation and of manoeuvre. At a distance of 18 m to the main road the average speed for all manoeuvre types per location is about the same, but starts at the general rule intersection a little bit lower than at the yield intersection, probably due to certain local differences between the minor roads. At the yield intersection the speed for both the left turn and the straight on manoeuvre decreases more during the approach than at the general rule intersection.

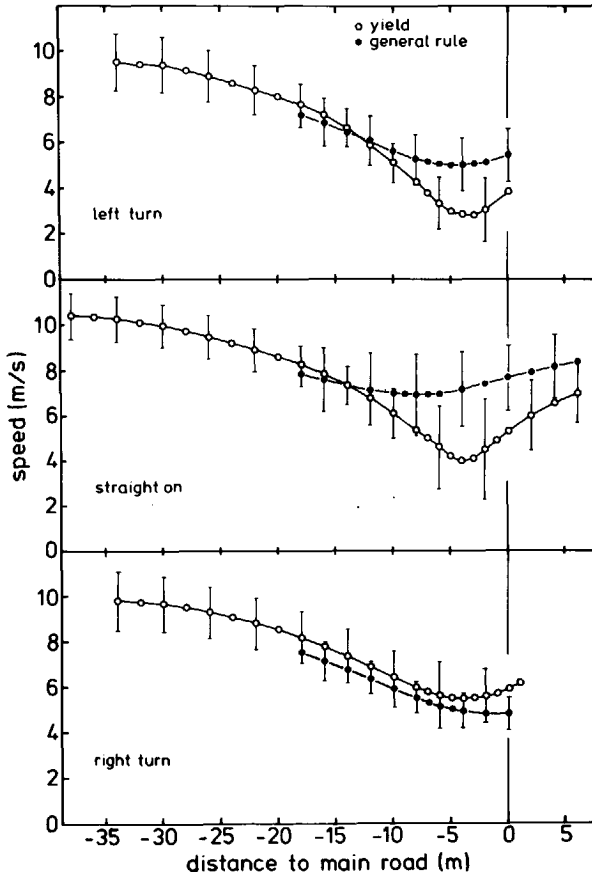


Fig. 4.11 Average speed profiles of free-moving cars by type of manoeuvre and type of priority regulation.

An ANOVA on the data of the right turn manoeuvre reveals that at the general rule intersection the speed is significantly lower than at the yield intersection ($p < 0.0001$, 3% explained variance), but that the shape of the speed curves doesn't differ (no interaction effect $P \times D$).

Similar to the analysis of the approaches at AKI railway grade crossings (Section 4.3.2) the **Time-To-Intersection (TTI)** measure is taken for comparison. As an example, Fig. 4.12 gives the TTI curves of individual approaches of left turning vehicles at both intersections. Two characteristic parameters of these TTI curves will be discussed in some more detail, viz. the TTI at the onset of braking (TTI_{br}) and the minimum TTI before actually entering the intersection (TTI_{min}).

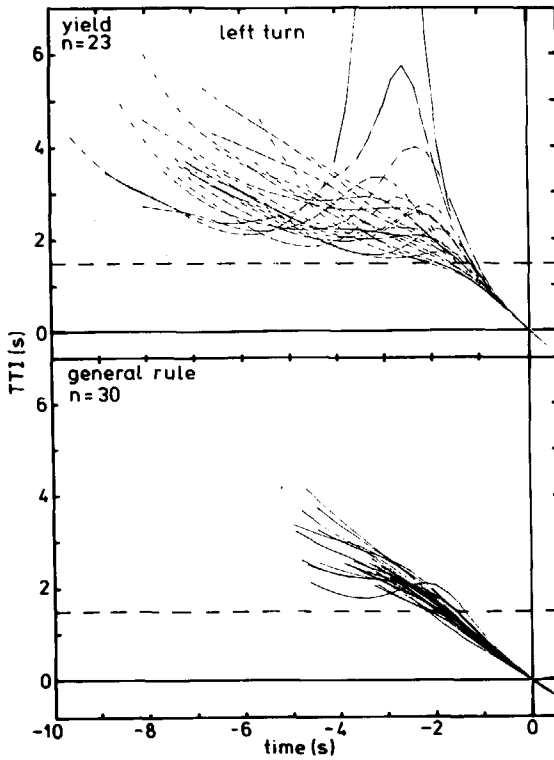


Fig. 4.12 Individual TTI curves of free-moving left turning cars at both intersections. At time = 0 s the main road is entered.

Time-To-Intersection at moment of braking (TTI_{br})

Because from the video recordings the moment of braking could not be deduced from the onset of the brake lights, a certain deceleration rate had to be set as a criterion for the moment of braking. To define the moment of braking a deceleration level of -1 m/s^2 is taken, generally occurring when releasing the throttle. At the general rule intersection, however, this criterion resulted in only 8% usable approaches, since on one hand 50% of the approaches already did exceed this level when entering the video scene, while on the other hand the remaining 42% did not exceed a deceleration level of -1 m/s^2 at all. So, unfortunately, TTI_{br} could only be used for comparing the type of manoeuvres at the yield intersection (Table IV). Although the left turn and straight on manoeuvre display a different speed at the moment of braking (t-test, two-tailed, $p < 0.05$) but not a significant difference in $DIST_{br}$, the mean TTI_{br} for both manoeuvre types is the same. The mean TTI_{br} of

the right turn manoeuvre is significantly lower than TTI_{br} of both the left turn and the straight on manoeuvre (Student t-test, two-tailed, $p < 0.01$), while only the mean $DIST_{br}$ of right turn and straight on differ significantly (t-test, two-tailed, $p < 0.01$). The results are shown in Fig. 4.13.

Table IV Mean and standard deviation (s.d.) of TTI_{br} (s), distance to main road $DIST_{br}$ (m) and speed V_{br} (m/s) at the moment of braking (acceleration $< -1 \text{ m/s}^2$) at the yield intersection.

	left turn (n = 15)		straight on (n = 27)		right turn (n = 22)	
	mean	s.d.	mean	s.d.	mean	s.d.
TTI_{br}	2.95	0.44	2.92	0.39	2.59	0.30
$DIST_{br}$	26.25	6.30	28.81	5.51	23.69	4.61
V_{br}	8.87	1.57	9.85	1.29	9.15	1.43

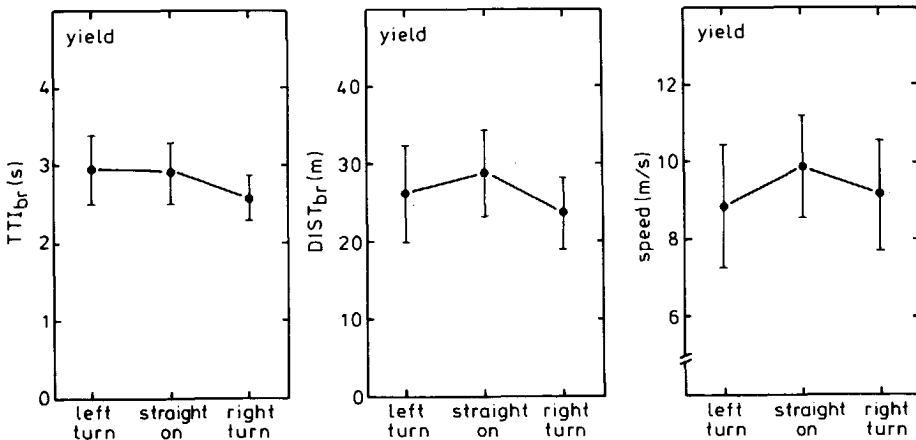


Fig. 4.13 Mean values of TTI_{br} , $DIST_{br}$ and V_{br} at the onset of braking by type of manoeuvre at the yield intersection. Bars give the standard deviations.

Minimum Time-To-Intersection (TTI_{min})

When an individual TTI curve has a minimum or an inflection point before actually entering the intersection (see Fig. 4.12) the driver decelerates to such an extent that, if necessary, he has ample opportunity to come to a halt. At the yield intersection this type of behaviour occurs more frequently than at the general rule intersection, in

particular for both the left turn and the straight on manoeuvre, see Table V. Only these manoeuvres at the yield intersection could be analysed in more detail.

Table V Percentage of approaches with a minimum TTI before entering the main road by type of manoeuvre and type of intersection (for absolute numbers see Table III).

	left turn	straight on	right turn	total
yield	65%	43%	7%	36%
general rule	10%	7%	0%	6%

The left turn manoeuvre appears to be more cautiously executed than the straight on manoeuvre; the minima of the TTI curves are higher, they occur at a greater distance from the main road and at a lower deceleration level, and also the entering speed at the main road is lower (Table VI).

Table VI Mean and standard deviation (s.d.) of TTI_{min} (s), and distance to main road (m), speed (m/s) and acceleration (m/s^2) at moment TTI_{min} occurs for left turn and straight on manoeuvres at the yield intersection; v_{ent} = entering speed at the main road (m/s).

	left turn (n = 15)		straight on (n = 13)		t-test (df=26)	
	mean	s.d.	mean	s.d.	t	
TTI_{min}	2.12	0.313	1.73	0.227	3.549	***
distance	10.68	2.167	8.49	1.457	2.970	**
speed	4.98	0.595	4.90	0.510	0.366	n.s.
acceleration	-2.26	0.349	-2.79	0.485	3.274	**
v_{ent}	3.22	0.723	4.08	0.542	3.393	**

n.s. not significant, ** $p < 0.01$, *** $p < 0.002$.

Only two of the total of 35 approaches that showed a minimum TTI had a $TTC_{min} < 1.5$ s (5.7%), both straight-on manoeuvres at the yield intersection. For almost all approaches the moment TTI_{min} occurred practically coincided with the moment of maximum deceleration. In 52% of the approaches with a TTI_{min} both moments

occurred within the same sample (0.24 s) and 84% displayed a difference of one sample or less. Apparently, the decision to proceed is closely related to the moment of minimum TTI.

An analysis of variance (ANOVA) of the entering speeds at the main road of the approaches without a minimum TTI before entering showed a main effect of type of manoeuvre ($p < 0.0003$, 23.5% explained variance) and an interaction effect between type of manoeuvre and type of priority regulation ($p < 0.01$, 12.5% explained variance). The effects are shown in Fig. 4.14.

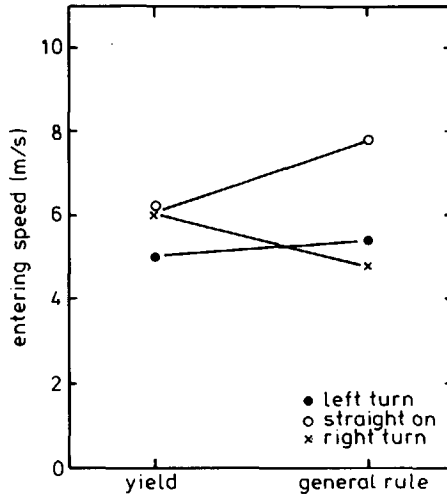


Fig. 4.14 Effects of type of manoeuvre and type of priority regulation on entering speed at main road of approaches from the minor road without a TTI_{min} .

Head movement patterns

Head movement patterns may give an indication of where attention is directed to and of what perception and decision-making strategy road users use during the approach of an intersection. In about 85% of the approaches of free-moving cars head movements could be scored satisfactorily. For each head movement during the approach the moment of the head movement and the direction (to the left or to the right) were registered from video. Because the pattern preceding an eventual decision to come to a halt is particularly interesting, the data only apply to that part of the approach where the vehicle still had a velocity of at least 1 m/s.

Fig. 4.15 gives for each type of manoeuvre and priority regulation the percentages of the approaches where no head movements, head movement(s) only to the left or to the right, or head movements in both directions were made. At the yield intersection all left turn and all straight on manoeuvres showed head movements in both directions, while at the general rule intersection in 39% and 28% of the approaches, respectively, head movements only occur in one direction. The right turn manoeuvre at the general rule intersection displays some approaches with no head movements at all or with head movements only to the right. At the yield intersection 25% of the right turning drivers only looks to the left.

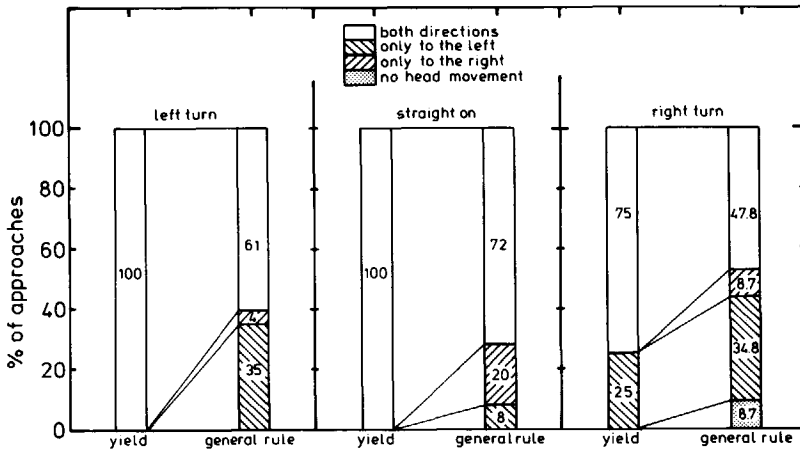


Fig. 4.15 Percentages of approaches with no head movements, and with head movements only to the left, to the right, or in both directions as affected by type of manoeuvre and by type of priority regulation.

At the yield intersection a second look in a given direction occurs more frequently than at the general rule intersection, viz. to the left in 69% vs. 14% and to the right in 56% vs. 28% of the approaches given a first look to the left or right, respectively. Also a third head movement in a given direction occurred more often at the yield intersection (15%) than at the general rule intersection (2%).

The average number of head movements per approach also appears to be higher at the yield intersection than at the general rule intersection (3.4 vs. 1.9, $p < 0.0001$, expl. var. 29.1%), see Fig. 4.16. Furthermore, the number of head movements differs with respect to the type of manoeuvre, viz. straight on has the highest number (3.2), followed by the left turn (2.6) and right turn manoeuvre (2.0), $p < 0.0001$, expl. var. 12.1%).

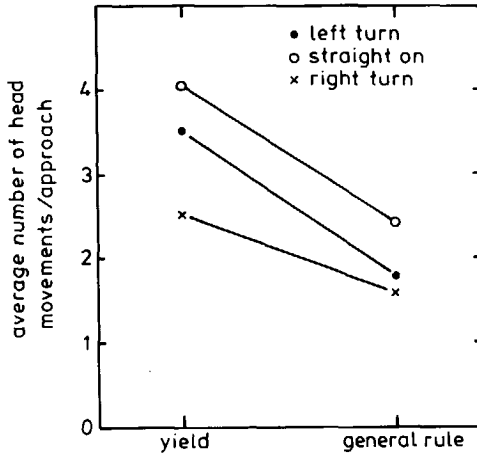


Fig. 4.16 Average number of head movements/approach by type of manoeuvre and type of priority regulation.

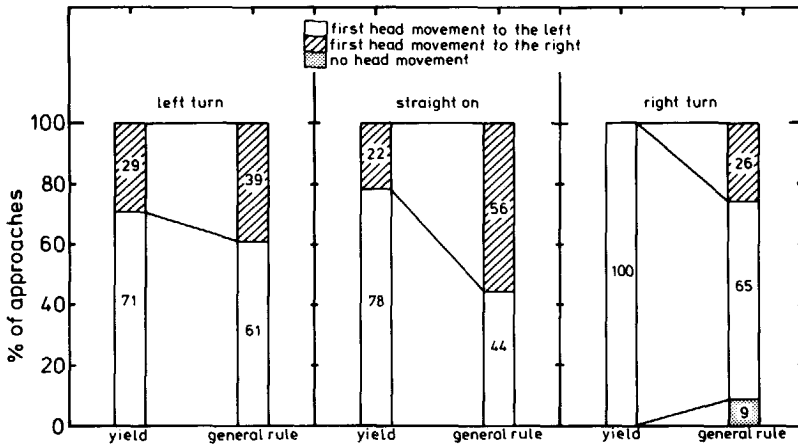


Fig. 4.17 Percentages of approaches with direction of first head movement by type of manoeuvre and type of priority regulation.

The direction of the first head movement might be an indicator of the initial priority in directing attention. At the yield intersection the first head movement to the left predominates the first head movement to the right (on an average 83% vs. 17%) and occurs more frequently than at the general rule intersection, see Fig. 4.17. At the latter, the frequencies of the first head movement to the left and to the right do not differ that much (on an average 56 vs. 41%).

TTI at moment of first head movement

The moment the first head movement occurs, may be an indication for the moment the searching for intersecting road users starts in the approach process. Therefore, the distance to the intersection ($DIST_{1st}$), speed (V_{1st}), and Time-To-Intersection (TTI_{1st}) at the moment of the first head movement have been determined for each individual approach. An ANOVA with dimensions type of priority regulation, type of manoeuvre, and direction of first head movement revealed the following results. The main effect of type of priority regulation (TTI_{1st} , $p < 0.01$, explained variance 5.8%; $DIST_{1st}$, $p < 0.0002$, expl. var. 13.7%; V_{1st} , $p < 0.02$, expl. var. 4.8%), appears to be caused by the first head movement to the left, resulting in an interaction effect between type of priority regulation and direction of the first head movement (TTI_{1st} , $p < 0.01$, expl. var. 6%; $DIST_{1st}$, $p < 0.001$, expl. var. 8.6%; V_{1st} , $p < 0.025$, expl. var. 3.6%). This effect is shown in Fig. 4.18. The priority regulation only differs with respect to the first head movement to the left; at the general rule intersection drivers start looking to the left at a shorter distance (both in time and in space) from the intersection than at the yield intersection. For none of the variables the first head movement was different with respect to type of manoeuvre.

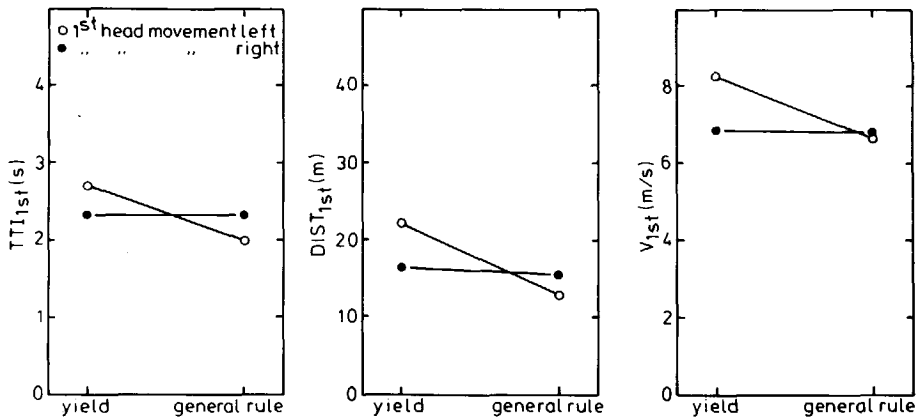


Fig. 4.18 Interaction effects of direction of first head movement and type of priority regulation on TTI, DIST, and V at the moment of the first head movement.

4.4.2 Intersections with separate bicycle tracks along the main road (The Hague)

Section 3.4.4 briefly described the study that was used to evaluate new geometric road design elements at non-signalised bicycle route intersections where bicyclists have the right-of-way over crossing traffic (experimental locations). At the experimental locations at The Hague special provisions are made to emphasise the presence of the cycle track parallel to the main road, such as a speed control hump, a lane

narrowing, deviant colour of the cycle track pavement, etc. To contrast road user behaviour as affected by these measures with that at intersections without special provisions, also three control locations with a standard lay-out were included in this study. For this comparison four experimental locations at The Hague (locations H1 through H4) were selected. The behaviour of free-moving cars approaching both from and towards the minor road (see Fig. 4.19) was analysed to estimate the effects of intersection lay-out and road design elements in terms of time related measures. A number of 379 approaches was available, subdivided by type of manoeuvre and type of location according to Table VII.

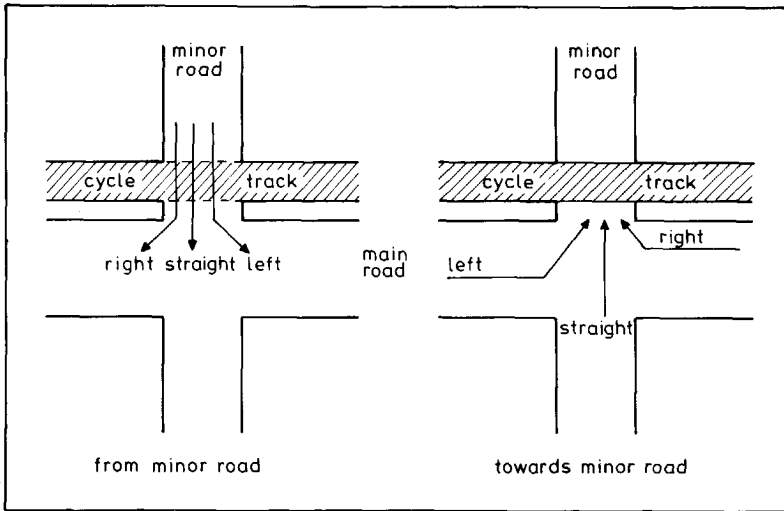


Fig. 4.19 Types of manoeuvres of cars crossing the cycle track from or towards the minor road at intersections with a separate cycle track along the main road.

Table VII Number of approaches of free-moving cars (n) from and towards the minor road by type of manoeuvre and type of location; N = number of locations within each group.

direction of crossing	type of location	left turn		straight on		right turn	
		N	n	N	n	N	n
from	experimental	4	28	2	21	4	50
	control	3	27	1	3	3	47
towards	experimental	3	37	1	10	3	45
	control	3	43	1	11	3	57
total			135		45		199

Speed profiles of free-moving cars

To evaluate the functioning of the special provisions at the experimental locations at The Hague, first of all, the speed profiles of free-moving cars coming from or going towards the minor road were compared with those at intersections where the lay-out is according the regular design standards for intersections with cycle tracks along the main road (control locations). Fig. 4.20 gives the average speed profiles of free-moving cars from and towards the minor road by type of manoeuvre at both experimental and control intersections as a function of the distance to the cycle track.

For each approach direction and each manoeuvre type a separate ANOVA was conducted with type of location (experimental vs. control) and distance to cycle track as dimensions. For the straight on manoeuvre from the minor road of the control locations no sufficient number of approaches was available. All speed profiles at the experimental locations are significantly lower than at the control locations (see Table VIII). The right turn manoeuvres displays an interaction effect between location and distance, indicating a different shape of the two speed profiles at experimental and control locations. At the experimental locations, the minimum speed is reached a few metres in front of the cycle track instead of on the cycle track at the control locations.

Table VIII Estimated percentages of explained variance from ANOVAs of the speed of free-moving cars from and towards the minor road for each type of manoeuvre. All effects are significant at the $p < 0.0001$ level (df = degrees of freedom).

	from				towards					
	left		right		left		straight		right	
	df	%	df	%	df	%	df	%	df	%
location (L)	1	16.7	1	7.7	1	21.9	1	23.5	1	20.7
distance (D)	24	45.8	22	54.7	14	6.8	24	38.3	14	12.8
L x D	24	-	22	1.0	14	-	24	-	14	4.3
error var.	1298	38.0	2063	36.6	1122	72.2	475	40.0	1488	62.2

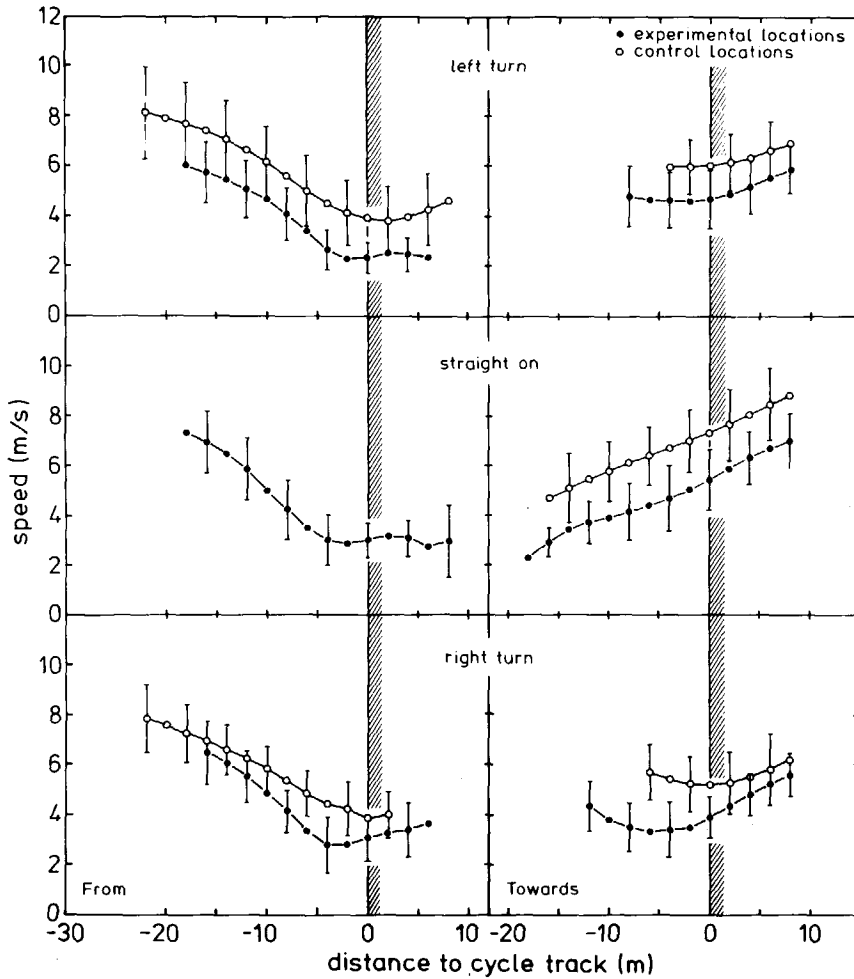


Fig. 4.20 Average speed profiles of free-moving cars from (left) and towards (right) the minor road at experimental bicycle route locations and control locations by type of manoeuvre.

Time-To-Intersection at moment of braking (TTI_{br})

For free-moving cars approaching from the minor road TTI curves were calculated relatively to both the cycle track and the main road. TTI_{br} (TTI at the moment the deceleration is exceeding the -1 m/s^2 level) could be determined in about 65% of the approaches at the experimental locations, and in 87% of the approaches at the control locations. Fig. 4.21 gives the results of the left turn and right turn manoeuvre. For the straight on manoeuvre no sufficient data were available.

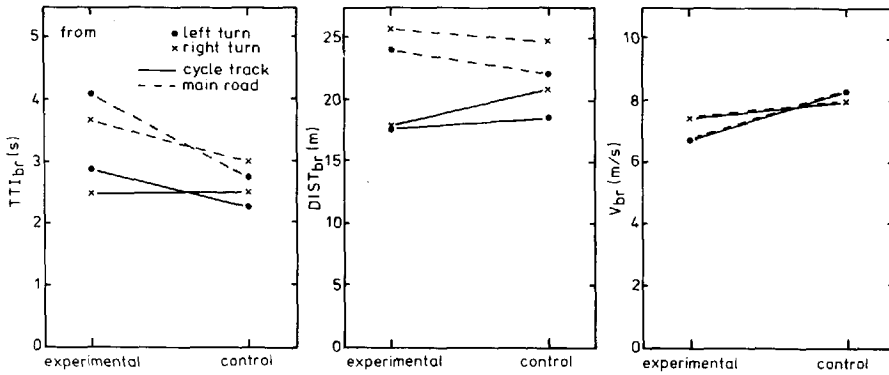


Fig. 4.21 Mean values of TTI_{br} , $DIST_{br}$, and V_{br} of free-moving cars approaching from the minor road relatively to the cycle track and the main road at experimental and control locations.

An ANOVA on TTI_{br} with three dimensions, viz. line to be crossed (cycle track or main road), location (experimental vs. control), and type of manoeuvre (left or right turn), reveals the following results. The main effect of line to be crossed ($F(1,217) = 78.6$, $p < 0.0001$, 22.9% of explained variance) is mainly due to the distance between cycle track and main road. At the onset of braking, more time is left at the experimental locations than at the control locations (the main effect of location explains 11.6% of the variance, $F(1,217) = 40.3$, $p < 0.0001$).

This effect is more pronounced for both TTI relatively to the main road (the interaction effect line to be crossed \times location accounts for 3.7% of explained variance, $F(1,217) = 13.7$, $p < 0.0001$) and the left turn manoeuvre ($F(1,217) = 13.5$, $p < 0.0005$, 3.7% of explained variance). An ANOVA on the distance to either the cycle track or main road at the onset of braking ($DIST_{br}$) only resulted in a main effect of line to be crossed ($F(1,217) = 33.2$, $p < 0.0001$, explained variance 13.8%). The speed at the onset of braking (V_{br}) is lower at the experimental than at the control locations ($F(1,217) = 23.8$, $p < 0.0001$, explained variance 10.2%) with a small interaction effect of type of manoeuvre ($F(1,217) = 4.25$, $p < 0.05$, explained variance 1.5%).

Both at the experimental and control locations only 31% of the approaches of free-moving cars towards the minor road displayed a deceleration that exceeded the -1 m/s^2 level. Moreover, only the right turn manoeuvre resulted in a sufficient number of approaches to compare both types of locations with respect to TTI_{br} . The results are given in Fig. 4.22.

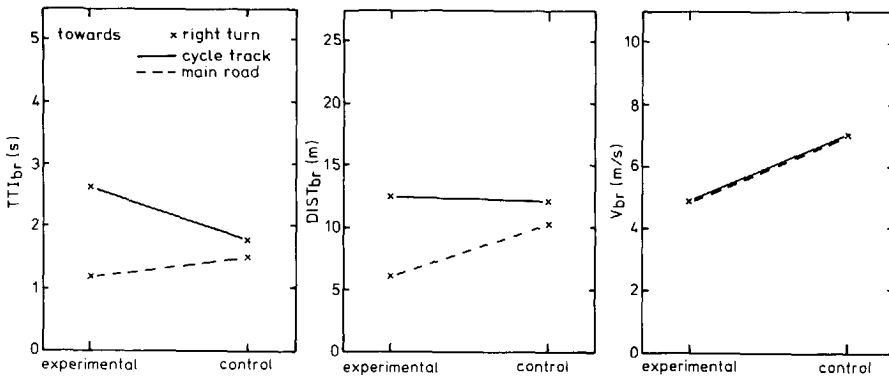


Fig. 4.22 Mean values of TTI_{br} , $DIST_{br}$, and V_{br} of free-moving cars towards the minor road relative to the boundary of the main road and to the cycle track at experimental and control locations.

Again, the main effect of line to be crossed ($F(1,90) = 78.4$, $p < 0.0001$, explained variance 37%) is obviously due to the distance between main road and cycle track. For the approaches towards the minor road at the experimental locations, TTI_{br} relatively to the cycle track reaches about the same level as for the approaches in opposite direction. At the control locations, the braking starts at about the same distance to the cycle track, but due to a higher speed, TTI_{br} is about 0.9 s lower than at the experimental locations.

Minimum Time-To-Intersection (TTI_{min})

On an average, at the experimental locations the approaches from the minor road display a TTI_{min} relatively to the cycle track in about 50% of the approaches, compared with only 10% at the control locations (see Table IX).

The TTI curves relatively to the main road more frequently display a minimum, viz. 87% of the approaches at the experimental and 32% at the control locations. Only the right turn manoeuvre enabled a comparison between experimental and control locations. The results are given in Fig. 4.23. ANOVAs of the three variables given reveal a main effect of line to be crossed. At both type of locations the TTI curves relatively to the main road display a larger minimum value than those relatively to the cycle track ($F(1,86) = 16.8$, $p < 0.0005$, explained variance 20.1%). At the experimental locations TTI_{min} relatively to the main road tends to be higher than at the control locations, but the interaction effect ($F(1,86) = 2.93$, $p < 0.09$, explained variance 2.5%) doesn't reach the $p < 0.05$ level of significance.

Table IX Percentage of approaches from the minor road with a minimum TTI before entering the cycle track and before entering the main road at experimental and control locations.

location	manoeuvre	total (100%)	cycle track	main road
experimental	left turn	28	39%	93%
	straight on	21	52%	86%
	right turn	49	55%	84%
total		98	49%	87%
control	left turn	27	4%	30%
	straight on	2	0%	50%
	right turn	47	15%	32%
total		76	10%	32%

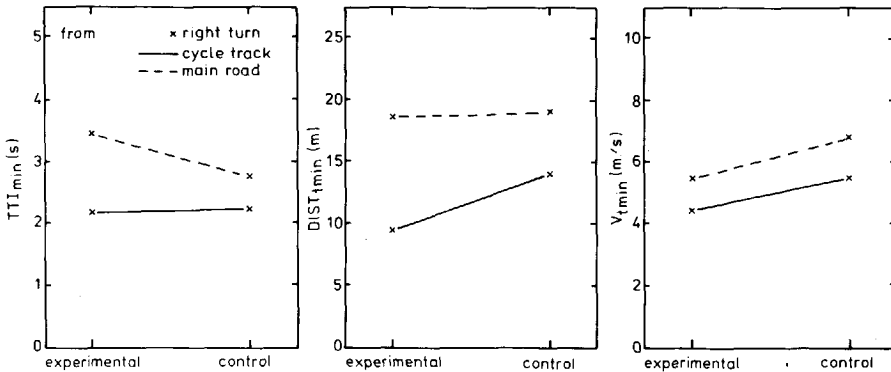


Fig. 4.23 Mean values of TTI_{min} relatively to the cycle track and to the main road, distance to cycle track or main road, respectively, at the moment TTI_{min} occurs ($DIST_{tmin}$), and V_{tmin} of free-moving right-turning cars approaching from the minor road at experimental and control locations.

$DIST_{tmin}$ only has a main effect of line to be crossed ($F(1,86) = 14.7$, $p < 0.0005$, explained variance 18.4%), whereas V_{tmin} also displays a main effect of location ($F(1,86) = 5.90$, $p < 0.02$, explained variance 7.1%). The deceleration at the moment of minimum TTI (ACC_{tmin}) only displays an effect of location (Fig. 4.24); at the

control locations, $ACC_{t_{min}}$ is higher than at the experimental locations ($F(1,86) = 4.75$, $p < 0.03$, explained variance 5.7%). Interestingly, at the experimental locations the moment of TTI_{min} relatively to the cycle track practically coincides with the moment of maximum deceleration (t_{dif} is about 0), whereas TTI_{min} relatively to the main road occurs earlier ($t_{dif} > 0$). At the control locations the moment of TTI_{min} relatively to the main road coincides with the moment of maximum deceleration, whereas TTI_{min} relatively to the cycle track occurs later than the maximum deceleration does ($t_{dif} < 0$). The main effect of location is significant at $p < 0.0005$ ($F(1,86) = 16.7$, explained variance 13.1%), the main effect of line to be crossed is significant at $p < 0.001$ ($F(1,86) = 12.3$, explained variance 18.2%).

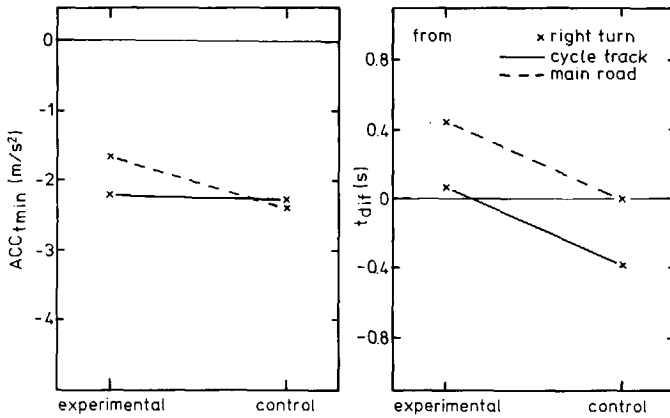


Fig. 4.24 Mean values of acceleration at the moment the TTI curves relatively to the cycle track or main road display a minimum ($ACC_{t_{min}}$) and t_{dif} , being the time difference between the moment of maximum deceleration and the moment TTI_{min} occurs.

Only at the experimental locations a sufficient number of approaches displayed a minimum TTI to compare the three type of manoeuvres. Fig. 4.25 and 4.26 give the results. All variables, but $V_{t_{min}}$, show a main effect of line to be crossed. The three types of manoeuvres only differ with respect to the speed at the moment TTI_{min} occurs ($F(2,128) = 3.77$, $p < 0.05$, explained variance 4.9%). For all manoeuvre types the moment of minimum TTI relatively to the cycle track occurs in close vicinity of the moment of maximum deceleration, on an average t_{dif} is 0.09 s.

As could be expected, the approaches in opposite direction (towards minor road) hardly displayed a TTI_{min} with respect to the border line of the main road, but also with respect to the cycle track a lower percentage of approaches with a TTI_{min}

occurred, being the highest at the experimental locations, viz. 22% versus only 4% at the control locations. No further analyses on the TTI data of the manoeuvres towards the minor road were conducted.

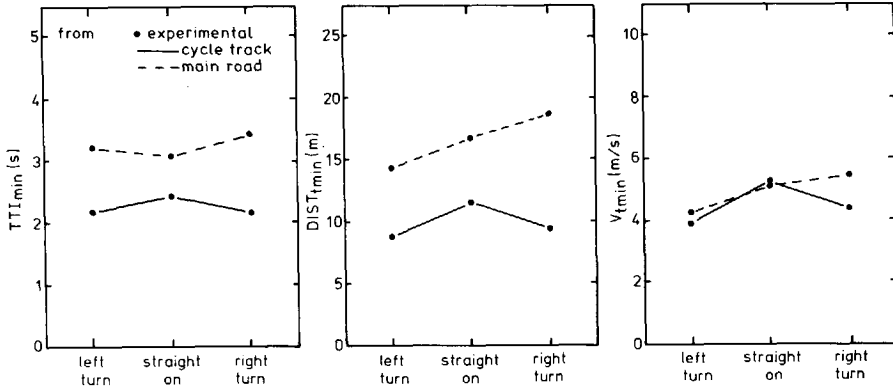


Fig. 4.25 Mean values of TTI_{min} relatively to the cycle track and to the main road, $DIST_{tmin}$, and V_{tmin} of free-moving cars approaching from the minor road at the experimental locations.

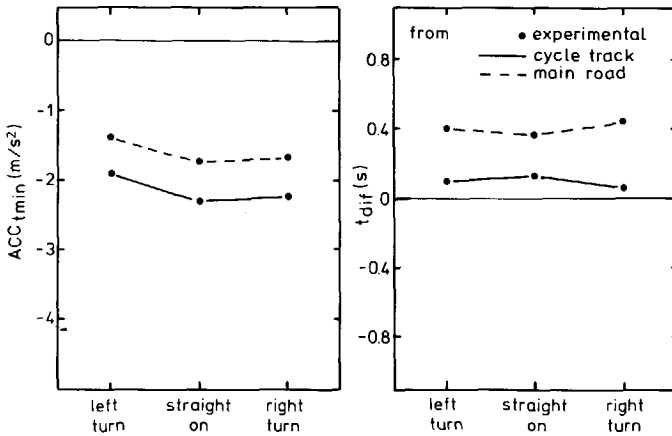


Fig. 4.26 Mean values of ACC_{tmin} and the difference in time between the moment of maximum deceleration and of TTI_{min} (t_{dif}).

4.4.3 Bicycle route intersections at Tilburg

The bicycle route intersections at Tilburg differ from the intersections of the bicycle route at The Hague, in that at the Tilburg locations cars only have to intersect with the bicycle track since no main road for motorised traffic is next to the cycle track.

One location (location T1) consists of a mid-block bicycle route road crossing (see Fig. 3.8). The main difference in lay-out between both approaches (lane width 3.5 m) at this intersection consists of the length of the median; one has a median of 50 m and the other one of 11 m. To investigate the influence of the length of the median, 50 approaches of free-moving cars were analysed.

At the locations T3 and T5, straight on going traffic from the minor road only crosses the cycle track (see Fig. 3.9 and Fig. 3.10, respectively). Both locations mainly differ with respect to priority regulation (T3 is a yield sign intersection and T5 a stop sign intersection), the intersection sight distance (at location T3 car drivers coming from the minor road have a good view close to the cycle track, at location T5 the view on the cycle track at the stop-line is very poor), and shape of speed control hump (T3 has two humps of moderate height, T5 has one rather high triangular bump of cobble pavement). Of course, the effects of these differences can not be investigated separately. At location T3 and T5, 29 and 27 approaches of free-moving straight-on going cars were analysed.

Speed profiles of free-moving cars

Fig. 4.27 gives the speed profiles of free-moving cars for both approaches at location T1. At the approach with the long median the average speed is significantly lower than at the short median (ANOVA, $F(1,1396) = 129.0$, $p < 0.0001$, explained variance 5.4%), but the average speed close to the cycle track is about the same.

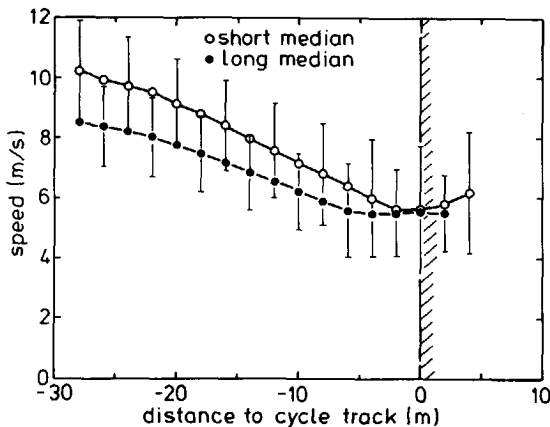


Fig. 4.27 Average speed profiles of free-moving cars at both approaches of bicycle crossing T1, one with a short median (11 m) and the other with a long median (50 m).

Fig. 4.28 gives the speed profiles of free-moving straight on going cars at the locations T3 and T5. Apart from the main effect of distance to the cycle track ($F(24,1330) = 82.7$, $p < 0.0001$, explained variance 56.7%) and the small main effect of location ($F(1,1330) = 32.8$, $p < 0.0001$, explained variance 0.9%), the interaction effect location \times distance ($F(24,1330) = 3.76$, $p < 0.0001$, explained variance 1.9%) indicates that the shapes of the curves significantly differ.

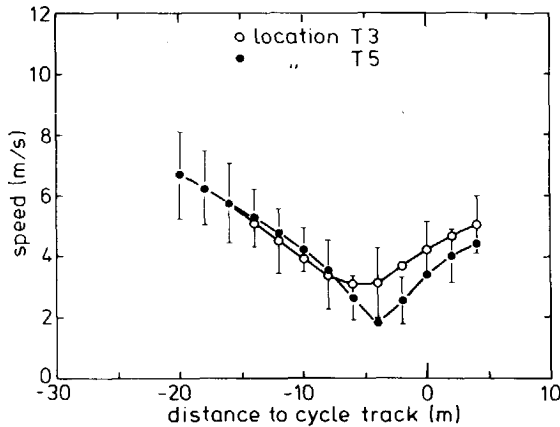


Fig. 4.28 Average speed profiles of free-moving cars approaching from the minor road at location T3 (yield sign, moderate view on cycle track, moderate speed control hump) and at T5 (stop sign, very restricted view, high hump of cobble pavement).

Time-To-Intersection at the onset of braking (TTI_{br})

The two approaches of bicycle crossing T1 differ with respect to the length of the median. The mean values of TTI_{br} , $DIST_{br}$, and V_{br} for both approaches are given in Table X. From ANOVAs on each variable it can be concluded that none of the variables significantly differs for the two medians. However, a statistical test on the difference between variances reveals that a long median considerably decreases the variability in TTI_{br} values (two-tailed test, $p < 0.05$, $F(11,15) = 3.46$).

At both intersections T3 and T5, the time to the cycle track at the onset of braking (TTI_{br}) could be determined for about 75% of the approaches of free-moving cars. The mean values are given in Table XI. ANOVAs on TTI_{br} and V_{br} did not result in significant differences between both intersections. At the intersection with the stop sign, restricted intersection sight distance, and high speed control hump (location T5) free-moving motorists started braking at a larger distance from the cycle track than drivers did at the other location T3 ($F(1,38) = 7.71$, $p < 0.01$, explained variance

14.4%). At location T3 a larger variability in TTI_{br} values occurs than at T5 (two-tailed, $p < 0.05$, $F(20,18) = 2.720$).

Table X Mean and standard deviation (s.d.) of TTI_{br} , distance to cycle track $DIST_{br}$, and speed V_{br} at the onset of braking (acceleration $< -1 \text{ m/s}^2$) of free-moving cars at both approaches of bicycle crossing T1 with a short (11 m) and a long (50 m) median, respectively; n is the number of approaches for which the given onset of braking could be determined.

	short median (n=16)		long median (n=12)		F-ratio	
	mean	s.d.	mean	s.d.		
TTI_{br} (s)	2.33	0.796	2.53	0.428	0.607	n.s.
$DIST_{br}$ (m)	20.64	6.233	20.07	4.975	0.062	n.s.
V_{br} (m/s)	8.94	1.580	7.96	1.674	2.350	n.s.

n.s. not significant at the $p < 0.05$ level.

Table XI Mean and standard deviation (s.d.) of TTI_{br} , distance to cycle track $DIST_{br}$, and speed V_{br} at the onset of braking (acceleration $< -1 \text{ m/s}^2$) of free-moving cars approaching from the minor road at location T3 (yield sign, moderate intersection sight distance, low speed control hump) and at T5 (stop sign, very restricted sight distance, high hump); n is the number of approaches for which the given onset of braking could be determined.

	T3 (n=21)		T5 (n=19)		F-ratio	
	mean	s.d.	mean	s.d.		
TTI_{br} (s)	3.03	0.729	3.22	0.442	0.967	n.s.
$DIST_{br}$ (m)	19.39	4.799	24.73	6.957	7.710	**
V_{br} (m/s)	6.67	1.791	7.69	2.117	2.570	n.s.

n.s. not significant at the $p < 0.05$ level, ** $p < 0.01$.

Minimum Time-To-Intersection (TTI_{min})

The TTI curves of free-moving cars approaching location T1 from the side with the short median only displayed a minimum in 7% of the approaches. Also very few approaches from the side with the long median had a TTI_{min} before entering the cycle track (12%).

On the contrary, a considerable number of the straight on manoeuvres at the locations T3 and T5 had a TTI_{min} before entering the cycle track, viz. 62 and 82%, respectively. On an average, at location T5 TTI_{min} is lower than at location T3, viz. 2.33 vs. 3.02 s ($F(1,38) = 10.8$, $p < 0.005$, explained variance 19.6%), and occurs at a shorter distance from the cycle track, 9.5 vs. 13.6 m ($F(1,38) = 8.85$, $p < 0.005$, explained variance 16.4%). At location T5 also the variability in TTI_{min} values is lower than at T3, the standard deviation being 0.396 and 0.895 s, respectively (two-tailed, $p < 0.01$, $F(17,21) = 5.108$). Again, the moment of TTC_{min} is closely related to the moment of maximum deceleration, with t_{dif} being 0.11 s at T3 and 0.14 s at T5.

4.5 Discussion and conclusions

Driver decision-making at traffic signals

At signalised intersections, the decision-making process at the guidance level of the driving task mainly consists of the stopping/non-stopping decision at the moment the signal changes from green to yellow. Most red light running offences appear to be related to this particular moment and, consequently, the duration of the yellow is of prime importance for this behaviour. In the literature, evidence was found that 4 s of yellow for 50 km/h intersections and 5 s for 80 km/h intersections would be optimum values [Van der Horst and Godthelp, 1982]. Compared with current practice in The Netherlands, such settings would imply a one second extension of the yellow phase. In the evaluation study it is found that, in spite of a small effect of habituation, this measure results in the number of run red offences by car drivers being cut in half (Table I). One year after the extension of the yellow no further change in behaviour is found compared with the 'six-month-after' period. A description of drivers' decision-making in terms of Time-To-Stop-line (TTS) is preferable over the Distance-To-Stop-line (DTS) for it accounts for the individual approach speed of vehicles. An equal probability of stopping or non-stopping occurs at a TTS value of 4 s. A probability of stopping between 0.2 and 0.8 is reached within a range of 3-5 s for TTS. An ideal probability function of stopping would have been a step function with a value of zero below a given TTS and a value of one above [Mahalel and Zaidel, 1985]. The probability of stopping as a function of TTS has a slightly steeper slope than the one as a function of DTS (with the legal approach speed of 50 km/h the latter would result in a time range between 2.8 and 5.8 s).

That type of traffic signal control influences drivers' decision-making is illustrated by comparing the probability of stopping functions at fixed-time and vehicle-actuated controlled intersections. At a vehicle-actuated controlled intersection drivers decide

to proceed in an earlier stage of the approach process. Given this dependency of behaviour on the type of traffic signal control, the hypothesis can be formulated that automobile drivers who are accustomed to vehicle-actuated control will adapt their behaviour and expect to be served when approaching the traffic signal during green. Therefore, when the green phase ends (that is, for example, the maximum green extension period has been reached), their expectancy is violated, with consequences for their decision-making processes [Alexander and Lunenfeld, 1986]. It is expected that similar effects will occur in other situations. For example, in a string of interconnected signalised intersections (progressive signal control systems), the experience at previous intersections generates the expectancy that the driver will have or will get green at the next one as well. Zegeer and Deen [1978] found a reduction of 54% in the number of run-red offences by applying a vehicle-actuated instead of fixed-time control. This reduction, however, may be mainly due to a much lower number of drivers that is exposed to the decision to stop or to proceed, since drivers' discipline at the red signal of vehicle-actuated controlled intersections actually appears to be less than that of fixed-time controlled ones.

Compared with drivers' behaviour at signalised road intersections, the red light compliance at AKI railway grade crossings appears to be much higher. At AKI crossings a probability of stopping of 0.5 is already reached at a TTS of 2.2 s instead of 4 s at vehicle-actuated controlled intersections or about 3 s at fixed-time ones. However, the greater willingness to stop at railway crossings also results in more critical behaviour, in that a number of stops could only be realised with an average deceleration rate of well over 4 m/s^2 and in some cases with a stop very close to the track. Such 'emergency' stops can easily lead to a stop on the track itself or to a rear end collision by a following car. Indeed, Wilde and Pearce [1979] reported that about 75% of all accidents near railway crossings are of this type. Although no crossings later than 6 seconds after the onset of the red signal were observed, it is imaginable that the ambiguous meaning of the red signal at railway crossings (both clear and stop) may cause crossings in a very late stage. When an unalerted driver approaches a railway crossing and suddenly discovers that the red signal is on, he might have the idea to encounter the beginning of red and decide to proceed. Several authors have argued that a separately signalised clearance interval with yellow might reduce these problems [Hauer, 1984; Heilmann, 1984; Van der Horst, 1988] and that a steady red signal would be preferred [NTSB, 1986; Tenkink and Van der Horst, 1988].

At AKI railway crossings a flashing white light indicates that no train is approaching. Behaviour of free-moving drivers approaching during this safe period also showed indications of uncertainty or lack of understanding of the signal. From TTI curves of individual approaches it can be concluded that about 2% of all approaches at one

AKI and 10% of the approaches at the other AKI decelerated to such an extent that a minimum TTI occurred before actually crossing the tracks. At signalised intersections it is very unlikely that drivers display such behaviour during the green phase. Even at yield intersections when drivers on the main road are confronted with a car coming from the minor road, a minimum TTI occurs less frequently, viz. in 2.4% of the approaches [Janssen and Van der Horst, 1988]. Head movements are a second indication of uncertainty. At AKI crossings 18 to 24% of free-moving drivers made head movements in both directions at least once, and 39 to 51% of the drivers felt confident to cross without making any head movements. Again, at a yield intersection only 4% of the drivers on the main road actually meeting a car from the minor road looked in both directions, while 62% did not make a head movement at all [Janssen and Van der Horst, 1988]. The cause of this uncertainty at AKI crossings may well be that the safe signal flashes, usually in traffic implying a warning.

Together with the finding by Tenkink and Walraven [1988] that the conspicuity of the light signals at railway crossings could easily be improved, it is concluded that the current signalisation at railway crossings is ripe for revision. A steady red signal preceded by a yellow interval of appropriate length is the minimum that should be strongly considered. Since traffic signals at signalised road intersections, railway grade crossings, and also at drawbridges demand the same behaviour from the road user, one uniform signalisation is recommended [Van der Horst, 1988].

Driver decision-making at non-signalised intersections

To negotiate non-signalised intersections drivers have to consider potential interactions with other road users. How they have to deal with them, depends highly on the type of priority regulation that applies at a given intersection. Studying the behaviour of drivers that approach an intersection when no other traffic is directly involved (free-moving cars), can give a sound judgment to what extent the type of priority regulation or the lay-out of an intersection itself contributes to their behaviour.

Yield vs. general rule intersection

Average speed profiles of free-moving cars approaching from the minor road appear to be dependent on the type of priority regulation (yield or general right-hand rule) and of manoeuvre (left turn, straight on, or right turn). At the yield intersection the speed for both the left turn and the straight on manoeuvre decreases much more than at the general rule intersection. For the right turn manoeuvre the shapes of the curves do not differ between both intersections, but the speed at the general rule intersection is a little bit lower, probably due to certain local differences between de minor roads.

TTI curves of individual approaches can be characterised by two parameters, viz. TTI_{br} and TTI_{min} . TTI_{br} is the TTI value at the moment braking starts, and gives an indication of how much time is left when drivers start the preparation of negotiating the intersection. To have a clear criterion the moment of braking is defined as the moment the deceleration is exceeding a level of -1 m/s^2 . At the yield intersection this level of braking is reached at about a TTI value of 3 s away from the main road (left turn and straight on). Right turning vehicles start braking a little later, viz. at a TTI of 2.6 s.

A TTI curve with a minimum TTI value (TTI_{min}) before actually entering the intersection enables the driver to gain time for interpreting the situation and, if necessary, to come to a complete stop. A prominent difference between the yield and general rule intersection consists of the number of approaches that actually displays a TTI_{min} before entering the main road. In particular, a substantial number of left turning and straight on going drivers approaches the yield intersection cautiously and, if necessary, is able to come to a stop (65 and 43% of the approaches, respectively). This behaviour is even more pronounced for drivers that turn left than the ones that go straight on. At the general rule intersection this type of behaviour occurs only for a few approaches (on an average, 6% of the approaches).

The pattern and number of head movements also appear to be dependent on the type of intersection. At the yield intersection drivers preponderantly start looking to the left and look out more frequently for other traffic than at the general rule intersection. The results for the left turn and right turn manoeuvre at the yield intersection are quite in line with the data Robinson et al. [1971] reported for the average number of head movements in approaches of a stop sign intersection when no other traffic was present, viz. 3.7 and 2.3, respectively. Only when the direction of the first head movement is to the left, both types of intersections differ with respect to the moment drivers start looking. Then, at the general rule intersection the first head movement is made at a TTI of 2 s away from the main road, instead of a TTI of 2.7 s at the yield intersection. To conclude, drivers generally display the type of behaviour that is minimally needed for conducting a given manoeuvre properly. Different approach strategies can be distinguished, dependent on the type of intersection one is approaching. This is in line with the ideas of, among others, Hale et al., [1988, 1989], that at a given type of intersection a specific programme of behaviour is started, having its own unique production rules. When at a given intersection the wrong programme is selected it may result in severe errors in operation and, consequently, this may be an important factor in the accident causation process.

Intersections with separate bicycle tracks along the main road

The functioning of special provisions at bicycle route intersections (experimental locations), such as a speed control hump, a lane narrowing, deviant pavement of

intersecting area of cycle track and minor road, etc., has been evaluated. Among other things, speed profiles of free-moving cars were compared with those at the same type of intersections without the special provisions to attract drivers' attention to the cycle track and its users (control locations). All speed profiles at the experimental locations are lower than at the control locations, but are, except for the right turn manoeuvre, of the same shape. The behaviour of car drivers approaching from the minor road (they have to cross the bicycle track first before entering the main road), has been analysed in more detail by means of the TTI measure relatively to both the cycle track and the main road. This analysis reveals that the special provisions at the experimental locations indeed address drivers' attention to the cycle track. The average TTI_{br} values relatively to the cycle track are similar to the TTI_{br} values that occur at the yield intersection without cycle tracks. Moreover, at the experimental locations about 50% of the approaches displays a TTI_{min} before actually entering the cycle track as opposed to only 10% at the control locations. At the experimental locations the three types of manoeuvre did not differ significantly with respect to average TTI_{min} values. For the right turning manoeuvres towards the minor road braking starts at a TTI of about 2.6 s, similar to the average TTI_{br} at the yield intersection without cycle tracks. At the control locations braking starts about 0.9 s closer to the cycle track. Relatively few approaches towards the minor road had a TTI_{min} before entering the cycle track. Generally, the drivers that cross the cycle track at the experimental locations behave similarly to those that approach a separate yield intersection. This also includes that the time margins relatively to the main road are greater. At the control locations the presence of the cycle track has not much influence on the approaching behaviour, implying that drivers' attention is more orientated towards the main road than to the cycle track.

Bicycle route intersections at Tilburg

A long median (length 50 m) at a mid-block bicycle route road crossings reduces the average approach speed as opposed to a short median of 11 m, but close to the cycle route the average speed is about the same. Although the average TTI_{br} does not differ significantly for both medians, a long median does reduce the variability in TTI_{br} values. At a mid-block crossing only a few approaches occur with a TTI_{min} before actually entering the cycle track.

The combination of a stop sign, a very restricted view on the cycle track, and a high hump of cobble pavement (location T5) induces a lower average speed close to the cycle track as compared to a combination of a yield sign, a moderate view, and two low speed control humps (location T3). At both intersections braking starts at a TTI of about 3 s away from the cycle track and the majority of approaches has a minimum TTI before entering the cycle track. The average TTI_{min} of about 3 s at location T3 is rather high, as is the variability in TTI_{min} values. Similar values occur at the

experimental locations (see before) relatively to the main road. So, this effect is probably occurring because of the presence of the first speed control hump at a distance of 10 m from the cycle track.

The Time-To-Intersection measure (TTI)

The analysis of drivers' behaviour in approaching several types of intersections reveals that a description in terms of TTI gives rather consistent results. First of all, the approaches can be objectively selected, in which drivers anticipate the potential presence of intersecting traffic, slow down, gain time for interpreting the situation, and, if necessary, are able to come to a halt. When this type of behaviour is displayed, the onset of braking (here defined as the moment the deceleration level exceeds a value of -1 m/s^2) in various situations appears to occur at a TTI of about 3 s away from the intersection. Because of the definition of the onset of braking as applied in this study, the moment the decision by the driver to do so, is made a little earlier. Of course, with outside-the-vehicle observations the moment the actual decision is made can not be directly observed. But based on studies on reaction times for braking [i.a. Johansson and Rumar, 1971; Richter and Hyman, 1974; Glencross and Anderson, 1976] it takes about 0.6 s for releasing the throttle and applying the brakes. Together with a mechanical response time of the brake system of about 0.4 s [Malaterre et al., 1987] the decision to start braking is made about one second earlier, or at a TTI of about 4 s away from the intersection. Interestingly, at signalised road intersections about 50% of the drivers that are a similar time away from the stop-line at the onset of yellow, decides to stop. The decision-making at AKI railway grade crossings appears to be rather deviant from this 'normal' behaviour, in that a probability of stopping of 0.5 is reached at a TTS of only 2.2 s.

The TTI at the moment the first head movement is made, varies between 2 and 2.7 s, dependent on both the type of priority regulation and the direction of looking, but, on an average, one starts looking for intersecting road users at a TTI of about 2.3 s away from the intersection. At about the same moment in the approach process the TTI curve reaches its minimum value. Only a few approaches have a TTI_{\min} less than 1.5 s. 95% of the approaches that display a TTI_{\min} have a value greater than 1.5 s. Interestingly, almost always the moment TTI_{\min} is occurring, practically coincides with the moment of maximum deceleration. Apparently, drivers estimate that the level of deceleration is sufficiently high at the moment TTI reaches its minimum. From this, the hypothesis can be formulated that a time measure such as TTI, apart from the function in deciding when to start braking, also plays an important role in the control of the braking process itself. In the next Chapters this point will be dealt with in more detail.

5 BEHAVIOUR IN INTERACTIONS WITH ROAD USERS

5.1 Introduction

In Chapter 4 road user behaviour has been analysed in relation with the 'static' environment in situations where no other traffic is directly involved. But an important part of the driving task at the guidance level consists of dealing with other road users. Then, apart from paying attention to his own movement, a road user has continuously to estimate the dynamic characteristics of the other road user involved who might react on his actions in return. Then, the advantages of describing this interactive behaviour by time related measures become even more prominent. In the following sections three time measures will be discussed in more detail. In Section 4.4.1 the behaviour of free-moving cars in relation to two types of priority regulation was analysed in terms of Time-To-Intersection (TTI). Also in interactions with other road users TTI can be used to describe behaviour of road users approaching an intersection, which enables a direct comparison with behaviour of free-moving cars. In Section 5.2 the study on the type of priority regulation is taken as an example of this approach. In Section 5.3 interactions between road users in several traffic situations are analysed in terms of the actual interaction measure Time-To-Collision (TTC). In situations where no direct collision course is present, the Post-Encroachment-Time (PET) is applied to define the proximity of the road users involved (Section 5.4). Finally, the results of this time-based analysis of interacting behaviour will be compared with subjective data on critical behaviour in road traffic as available from the two international calibration studies on Traffic Conflicts Techniques (Section 5.5).

5.2 Time-To-Intersection (TTI)

Section 3.4.3 described the study in which two types of priority regulation, viz. yield sign regulation and general right-hand right-of-way rule, were compared. In the Netherlands there is one exception on the general rule of traffic from the right has the right-of-way, viz. bicyclists or moped riders have to give the right of way to motor vehicles on the intersecting road. In this study a total of 644 encounters was analysed quantitatively from video, subdivided by type of encounter, priority regulation, and of manoeuvre according to Table XII. As indicated in Section 3.4.3, only encounters between a car from the minor road and a car or bicycle on the major road were selected. Complex encounters with more than two road users involved were not included in the analysis.

Table XII Number of observed encounters among cars coming from the minor road and road users on the main road (car/bicycle) by type of priority regulation (yield/general rule), and type of manoeuvre of minor road cars (left turn/straight on/right turn).

	left turn		straight on		right turn		total
	car	bicycle	car	bicycle	car	bicycle	
yield	55	17	193	48	109	35	457
general rule	43	38	40	28	19	19	187
total	98	55	233	76	128	54	644

Since the selection of both intersections was, among other things, based on similar traffic volumes and manoeuvre patterns, the big difference in the number of selected encounters between both intersections is remarkable. At the general rule intersection, also much less complex encounters occurred than at the yield intersection. Janssen and Van der Horst [1988] give the plausible explanation that a yield regulation "collects" more encounters by the fact that road users at the minor road more frequently decide to slow down when they are initially ahead of road users on the main road.

For both vehicles involved in an encounter, TTI curves were calculated by dividing the instantaneous distance to the intersection area (defined as the distance to a given reference line dependent on the approach direction, see Fig. 5.1) by the instantaneous speed.

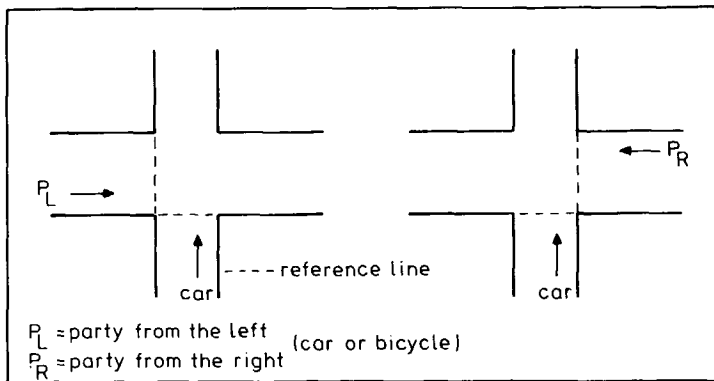


Fig. 5.1 Definitions of reference lines for calculating TTI dependent on approach direction.

As an example, Fig. 5.2 gives the individual TTI curves of straight-on going cars from the minor road involved in an encounter with traffic from the left on the main road at the yield intersection. Similar to the analysis of approaches of free-moving cars (Section 4.4.1), both the TTI value at the onset of braking and the minimum TTI, if any, as reached during the approach will be used to relate road user behaviour in encounters to the intersection geometry.

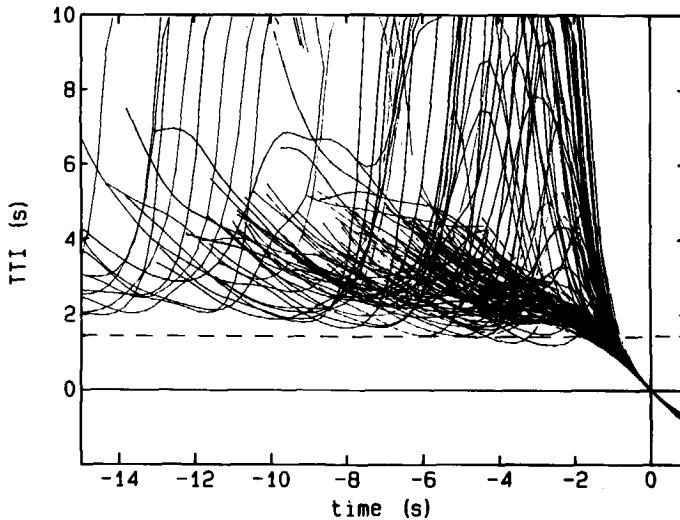


Fig. 5.2 Individual TTI curves of straight-on going cars from the minor road at the yield intersection involved in an encounter with traffic from the left.

5.2.1 Time-To-Intersection at the onset of braking (TTI_{br})

Unfortunately, at the general rule intersection, TTI_{br} could not be determined in 44% of the minor road approaches, since the criterion level for braking of -1 m/s^2 was already exceeded when entering the video scene. On the other hand, 24% of the approaches did not exceed this deceleration level at all before entering the intersection area. Because of this, the data of the general rule intersection could not be included in the TTI_{br} analysis. At the yield intersection, 94% of the minor road approaches reached a deceleration of -1 m/s^2 . Therefore, only the yield intersection TTI_{br} data were analysed in more detail.

In encounters with traffic on the main road, neither TTI_{br} , nor $DIST_{br}$ or V_{br} differ significantly by type of manoeuvre, type of party on the main road, or the approach direction of the party, see Fig. 5.3 and 5.4.

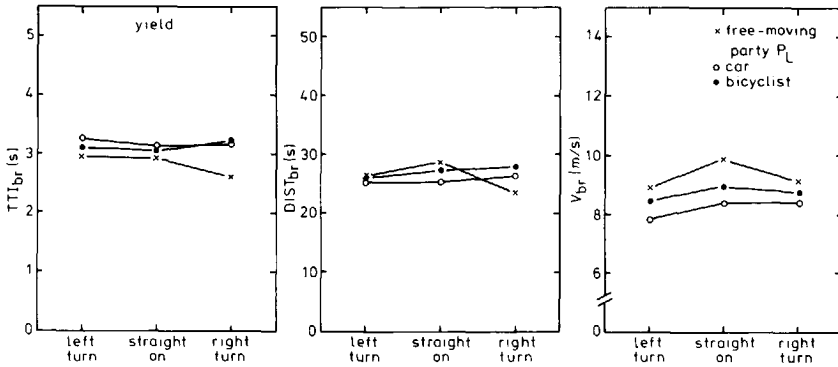


Fig. 5.3 Mean values of TTI_{br} , $DIST_{br}$ and V_{br} at the onset of braking by cars approaching from the minor road by type of manoeuvre and by type of party from the left on the main road at the yield intersection.

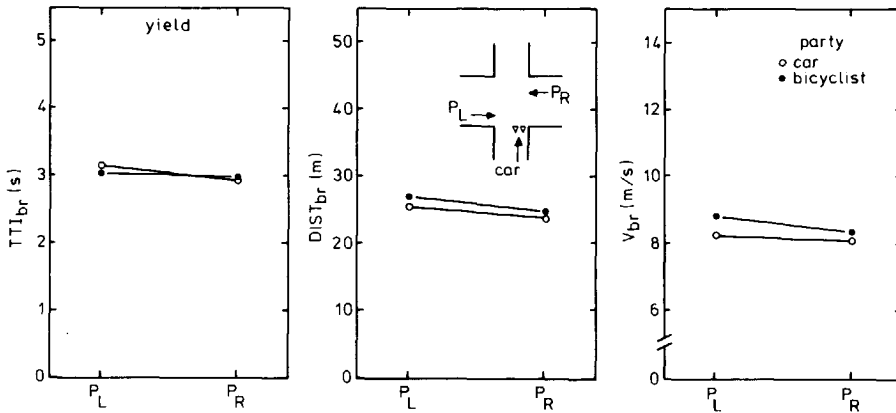


Fig. 5.4 Mean values of TTI_{br} , $DIST_{br}$ and V_{br} at the onset of braking by minor road cars (only left turn and straight on) by type of party on the main road and by party's approach direction at the yield intersection (P_L , P_R = party is approaching from the left or right, respectively).

By comparing the data of encounters with that of free-moving cars, however, it appears that free-moving car drivers from the minor road display a lower average TTI_{br} than in an encounter (ANOVA, $F(1,275) = 14.6$, $p < 0.0005$, 7.5% of explained variance) due to a higher speed ($F(1,275) = 9.24$, $p < 0.005$, 4.5% of

explained variance). The presence of another party on the main road does not effect the distance at which TTI_{br} occurs.

A comparison of the cumulative distributions of cars approaching from the minor road with and without a party on the main road reveals similar results. The cumulative distributions of both TTI_{br} and V_{br} significantly differ (Kolmogorov-Smirnov test, two-tailed, level of significance $p < 0.002$ and $p < 0.001$, respectively), while the distributions with respect to $DIST_{br}$ do not, see Fig. 5.5. In less than 4% of the approaches braking starts closer than 2 s away from the intersection.

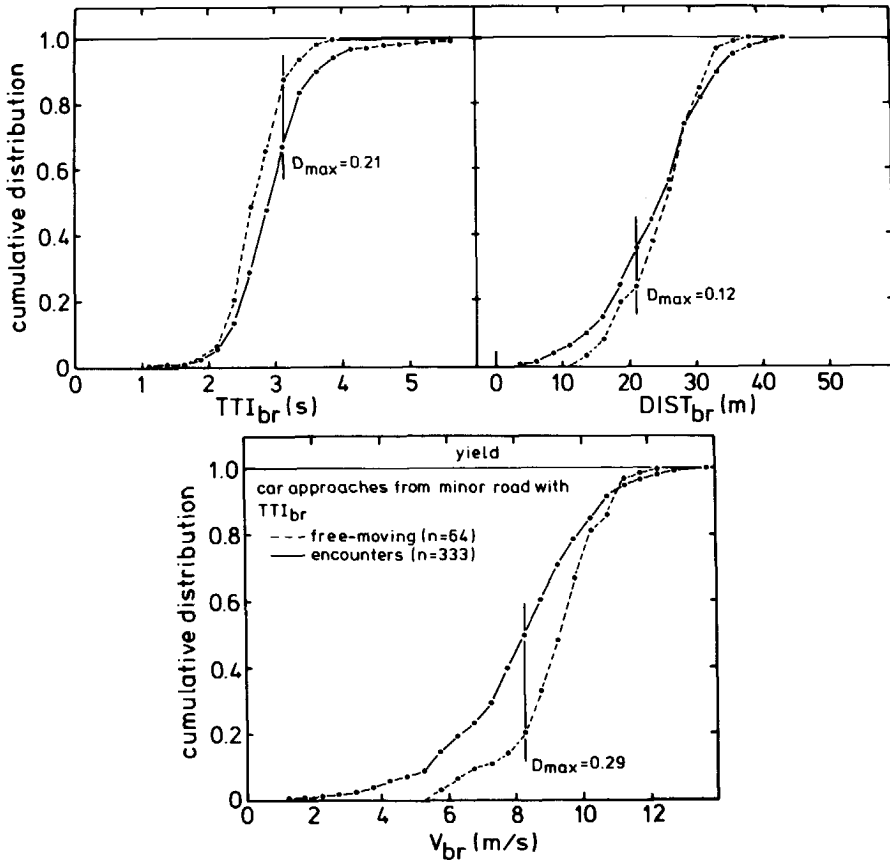


Fig. 5.5 Cumulative TTI_{br} , $DIST_{br}$, and V_{br} distributions of car approaches from the minor road at the yield intersection with and without parties on the main road (type of manoeuvre and type of party combined).

As can be expected, the number of main road cars exceeding a deceleration level of -1 m/s^2 in encounters with cars from the minor road, is rather low compared with the number of braking cars at the minor road (12% vs. 72%, respectively). If a main road car brakes, braking starts at the same distance to the intersection, but at a higher speed (Kolmogorov-Smirnov test, two-tailed, $p < 0.001$) resulting in a much lower TTI_{br} ($p < 0.001$), see Fig. 5.6.

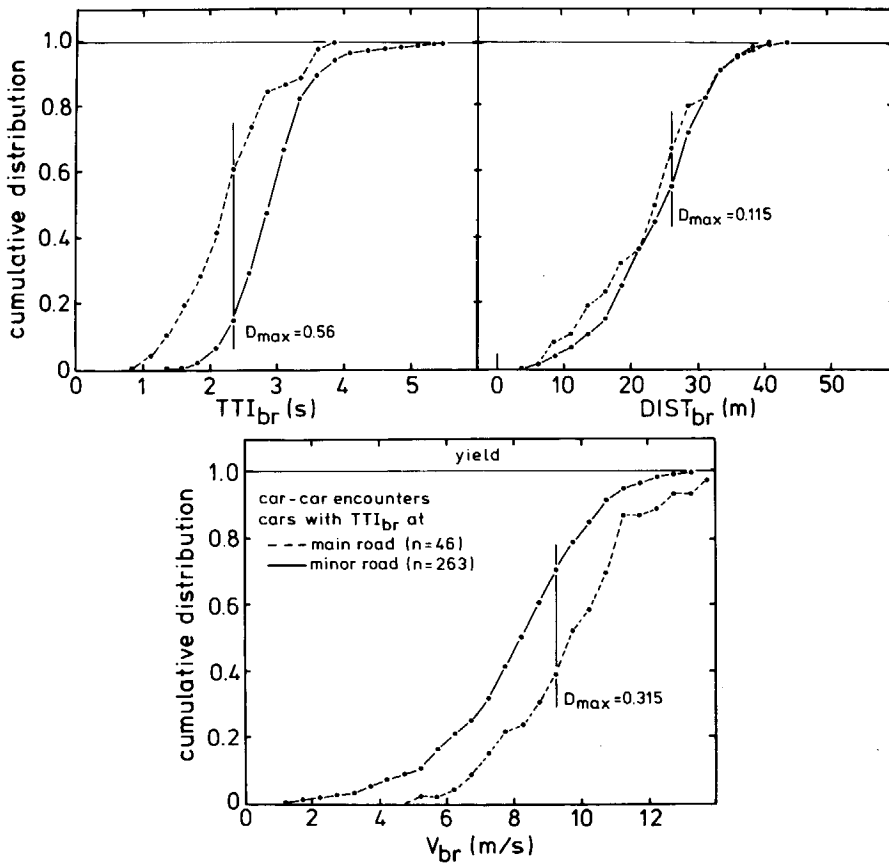


Fig. 5.6 Cumulative TTI_{br} , DIST_{br} , and V_{br} distributions of cars from the minor road and from the main road that brake in car-car encounters at the yield intersection.

So far, the variables TTI_{br} , DIST_{br} , and V_{br} were separately presented, but, of course, they are interrelated to each other. It seems reasonable to assume that the speed which a driver is approaching an intersection with, can be regarded as the independent variable. Then, given a certain speed, the decision to start braking,

might be either based on the distance or the time to the intersection. As an example, Fig. 5.7 gives the scatterdiagrams of both $DIST_{br}$ and TTI_{br} as a function of V_{br} for all minor road cars involved in an encounter.

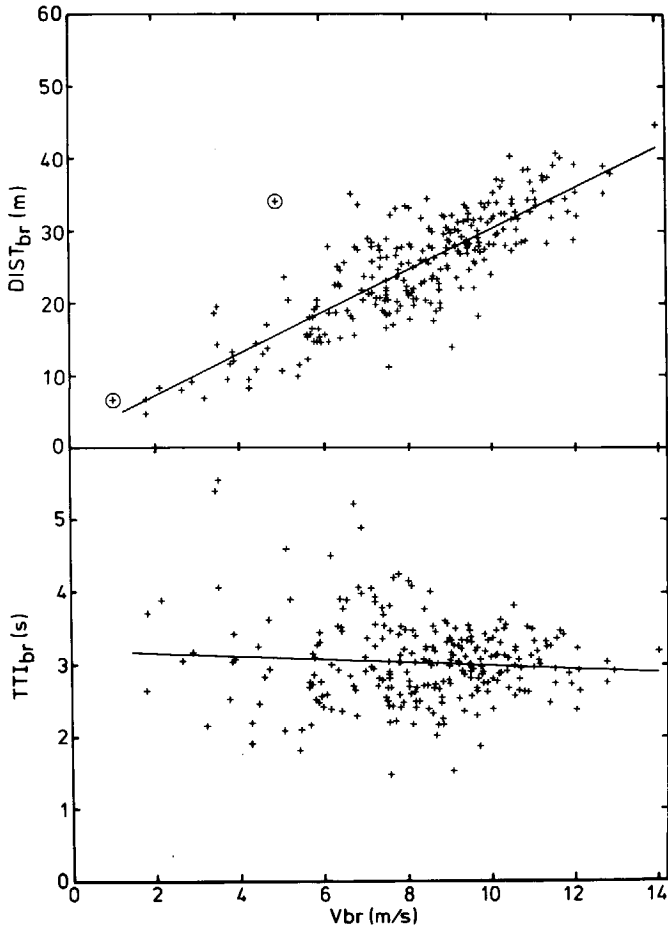


Fig. 5.7 Scatterdiagrams of $DIST_{br}$ (top) and TTI_{br} (bottom) with V_{br} of decelerating cars approaching from the minor road and involved in an interaction with a road user on the main road.

$DIST_{br}$ appears to be highly correlated with V_{br} (Pearson product-moment correlation coefficient $r = 0.83$, $p < 0.0001$) with the corresponding linear regression equation:

$$DIST_{br} = 1.49 + 2.86 * V_{br} \quad (3)$$

TTI_{br} displays a small correlation with V_{br} ($r = -0.17$, $p < 0.01$), but after excluding only 2 approaches with a TTI_{br} greater than 6 s (the two marked points at the top figure), this correlation is not significant anymore ($r = -0.09$, $p < 0.16$). Similar results occur for free-moving cars approaching from the minor road or decelerating cars at the main road, that are involved in an encounter, see Table XIII.

Table XIII Correlations and regression coefficients of relations $DIST_{br} - V_{br}$ and $TTI_{br} - V_{br}$, respectively. A: decelerating cars approaching from minor road, involved in an encounter; B: decelerating cars approaching from the main road, involved in an encounter; C: free-moving cars from the minor road.

	n	$DIST_{br}$				TTI_{br}			
		r	p	intercept	slope	r	p	intercept	slope
A	262	0.83	0.000	1.49	2.86	-0.09	0.15	3.24	-0.02
B	46	0.61	0.000	1.02	2.30	0.19	0.21	1.82	0.06
C	64	0.76	0.000	-2.24	3.06	0.13	0.29	2.46	0.04

5.2.2 Minimum Time-To-Intersection (TTI_{min})

Table XIV gives the number of approaches that display a TTI_{min} before entering the intersection area at both intersections. A log-linear model analysis is used to investigate the effects of type of priority regulation, type of manoeuvre, type of party, approach direction of party, and having the right of way (at the general rule intersection) on the proportions of approaches with a TTI_{min} , Fig. 5.8a. Fig. 5.8b gives the results of a log linear model fit with the dimensions type of priority regulation, type of party from the left, and type of manoeuvre, on the proportions of cars approaching from the minor road ($\chi^2 = 8.82$, $df = 12$, $Q = 0.718$).

From this analysis it can be concluded that:

- at the yield intersection the approaches from the minor road more frequently display a TTI_{min} than at the general rule intersection where the party on the major road formally has to give the right of way,
- the proportion of approaches with a TTI_{min} is dependent on the type of manoeuvre, the right turning manoeuvre having the lowest and the left turn having the highest number of TTI_{min} approaches, and
- the number of TTI_{min} approaches is much higher when a party is present on the major road than for free moving cars. It does not matter whether the party is a car or a bicyclist.

Table XIV Number of approaches with (Y) and without (N) a TTI_{min} before entering the intersection area by type of priority regulation, of party involved, and of manoeuvre.

intersection	road user	other party	left turn		straight on		right turn		
			Y	N	Y	N	Y	N	
yield	car on minor road	P_L car	21	7	71	26	55	54	
		P_R car	23	5	76	22	-	-	
		P_L bicycle	6	3	20	7	16	19	
		P_R bicycle	6	2	14	7	-	-	
	P_L car	car on	2	13	1	218	-	-	
	P_R car	minor road	1	48	0	68	-	-	
	P_L bicycle		2	5	0	63	-	-	
	P_R bicycle		4	9	5	11	-	-	
	general rule	car on minor road	P_L car	8	18	4	18	1	18
			P_R car	14	3	9	8	-	-
P_L bicycle			6	9	2	6	1	18	
P_R bicycle			3	10	5	15	-	-	
P_L car		car on	1	0	34	32	-	-	
P_R car		minor road	1	18	1	12	-	-	
P_L bicycle			0	4	11	37	-	-	
P_R bicycle			3	15	0	13	-	-	

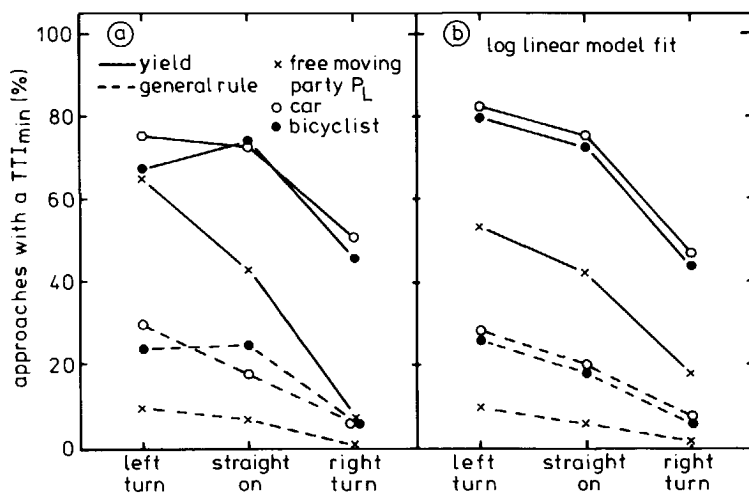


Fig. 5.8 Proportions of approaches by cars from the minor road with a TTI_{min} before entering the intersection area by type of priority regulation (yield/general rule), type of party from the left (car/bicyclist/none), and type of manoeuvre (left turn/straight on/right turn). In Fig. 5.8a the original proportions are given; Fig. 5.8b gives the results of a log linear model fit.

A log linear model analysis on the number of approaches by cars from the minor road at the yield intersection with and without a TTI_{min} reveals that neither the type of manoeuvre (left turn or straight on) nor the type of party (car or bicycle) or its direction (from the left or right) is relevant to the proportion of approaches with a TTI_{min} ; a model with a constant proportion of 75% satisfactorily describes all conditions ($\chi^2 = 3.51$, $df = 11$, $Q = 0.982$). At the general rule intersection the interaction between type of party and the direction from which the party is approaching is needed to get a good fit ($\chi^2 = 9.28$, $df = 6$, $Q = 0.158$). The results are given in Fig. 5.9. It appears that the proportion of car approaches with a TTI_{min} properly reflects whether one has the right of way, viz. giving the right of way to cars from the right, and having the right of way over cars from the left and bicyclists from the left or from the right.

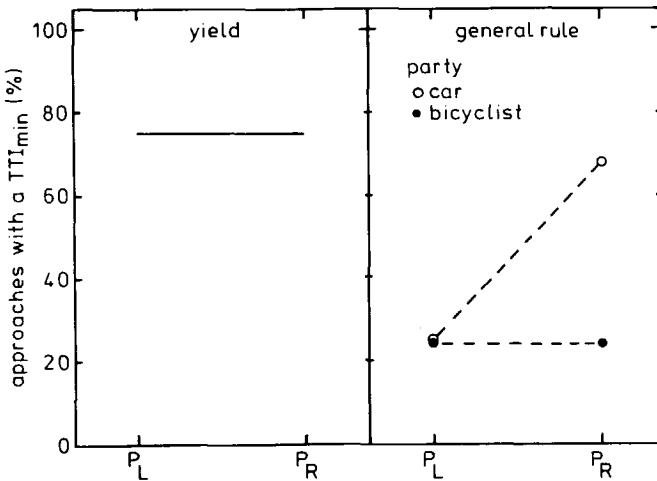


Fig. 5.9 Results of a log linear model fit on the proportions of TTI_{min} approaches by cars from the minor road (left turn and straight on manoeuvre combined) before entering the intersection area at the yield intersection (Fig. 5.9a) and general rule intersection (Fig. 5.9b) by type of party on the main road (car/bicyclist) and its approach direction (from the left P_L /from the right P_R).

Having the right of way at the yield intersection results in very few TTI_{min} approaches, only 1.1% of all car approaches on the main road shows a TTI_{min} before entering the intersection area. At the general rule intersection, apart from the formal priority regulation, also the character of the road influences driver approach behaviour. A log linear model analysis on the number of car approaches with and without a TTI_{min} with the factors type of manoeuvre (left turn/straight on), right of way

(yes/no), and type of road ('major'/'minor') reveals that having the right of way considerably reduces the proportion of TTI_{min} approaches, but also that approaching from the 'minor' road more frequently results in a TTI_{min} ($\chi^2 = 7.08$, $df = 5$, $Q = 0.215$), see Fig. 5.10. No differences between the left turn and straight on manoeuvre are found.

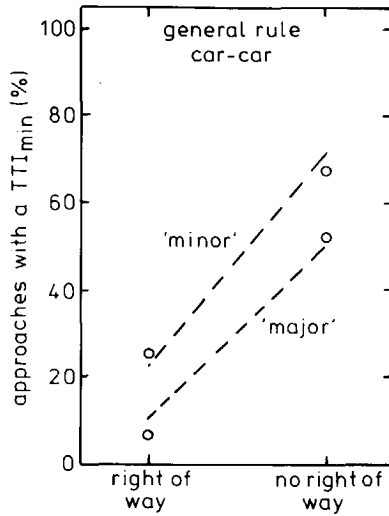


Fig. 5.10 Results of a log linear model fit on the proportion of car approaches with a TTI_{min} at the general rule intersection (left turn and straight on manoeuvres combined) by right of way and character of the road.

The mean TTI_{min} of all car approaches having a TTI_{min} and involved in an encounter ($n=402$) is 2.39 s with a standard deviation of 0.71 s. Only 10% has a TTI_{min} less than 1.5 s, see Fig. 5.11. The 15th percentile value is 1.67 s and the median value 2.14 s.

At the yield intersection minor road driver behaviour in encounters with traffic on the main road appears to be rather consistent with respect to TTI_{min} ; ANOVAs reveal that there are no effects of type of manoeuvre, the type of road user involved, or the direction the party is coming from, Fig. 5.12. However, if free-moving cars have a TTI_{min} before entering the main road, on an average, they have a lower TTI_{min} than in encounters with other road users (ANOVA, ($F(1,142) = 10.7$, $p < 0.002$, 10% of explained variance)).

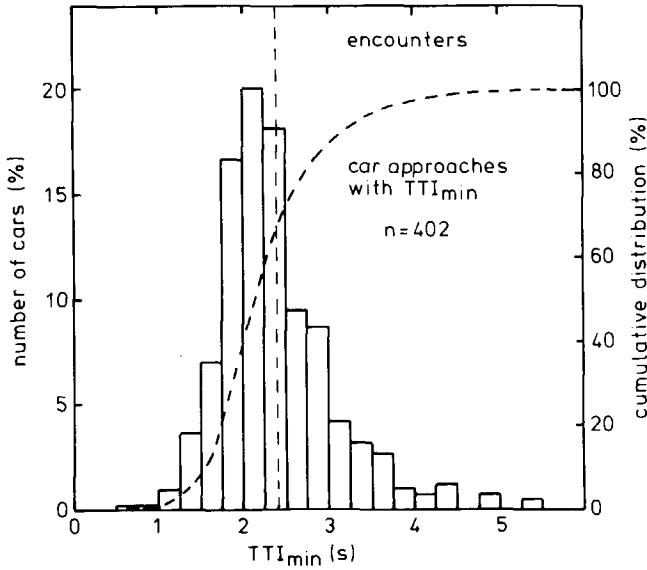


Fig. 5.11 TTI_{min} distribution of all car approaches at both intersections having a TTI_{min} and involved in an encounter. The right scale relates to the cumulative distribution.

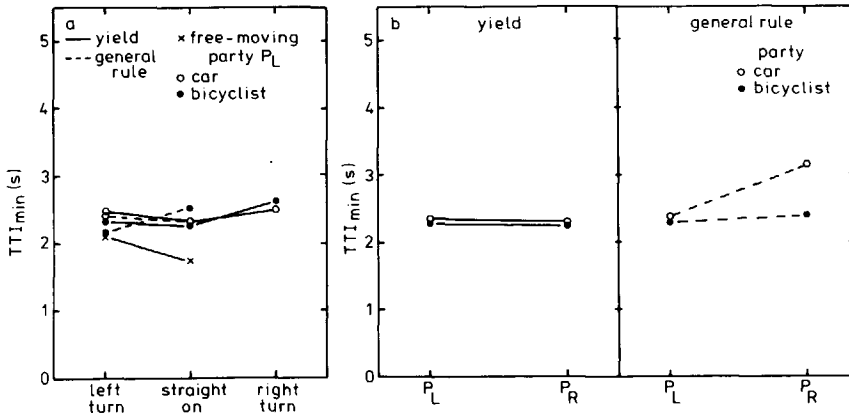


Fig. 5.12 Mean TTI_{min} for cars approaching from the minor road by type of manoeuvre (left turn/straight on/right turn) and type of party from the left (car/bicyclist), Fig. 5.12a, and by party's approach direction (left/right), left turn and straight on manoeuvre combined, Fig. 5.12b.

Also a Kolmogorov-Smirnov test on the cumulative TTI_{min} distributions of free-moving cars and cars involved in an encounter reveals the same result (two-tailed, $D_{max} = 0.341$, $p < 0.005$), Fig. 5.13. The few car approaches on the main road with a TTI_{min} ($n = 4$), all had a TTI_{min} lower than 1.5 s, on an average 1.1 s with a standard deviation of 0.29 s.

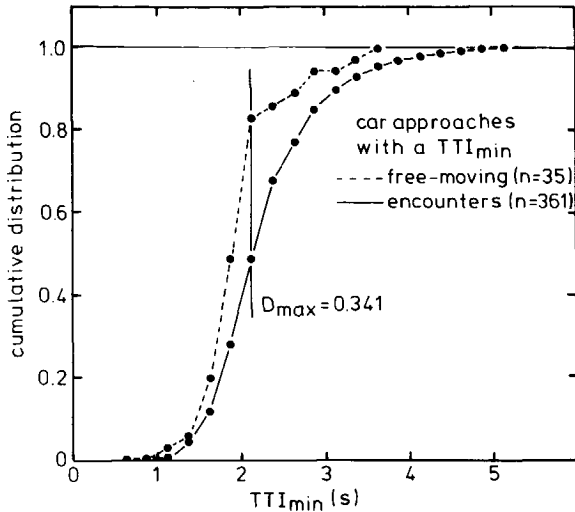


Fig. 5.13 Cumulative TTI_{min} distributions of free-moving cars and cars involved in an encounter approaching from the minor road at both intersections.

At the general rule intersection, the behaviour of 'minor' road car drivers with respect to TTI_{min} seems to be more dependent on the right of way. If they have the right of way (in encounters with cars or bicycles from the left or with bicycles from the right) similar mean TTI_{min} values occur as at the yield intersection. But if they have to give right of way to cars from the right, the mean TTI_{min} appears to be higher (t-test, two-tailed, $t = 2.16$, $df = 33$, $p < 0.05$), Fig. 5.12b. Also compared with the mean TTI_{min} value of car drivers on the 'major' road that have to give way to cars from the left, TTI_{min} of 'minor' road drivers appears to be high (t-test, two-tailed, $df = 55$, $p < 0.02$), Fig. 5.14.

For cars approaching from the minor road and involved in an encounter, the moment TTI_{min} occurs, is closely related to the moment of maximum deceleration; on an average, the difference between both moments is only 0.14 s. Compared with free-moving cars, the moment of maximum deceleration occurs somewhat later. According

to the Kolmogorov-Smirnov test both cumulative distributions of Fig. 5.15 significantly differ at the $p < 0.001$ level with a $D_{\max} = 0.371$.

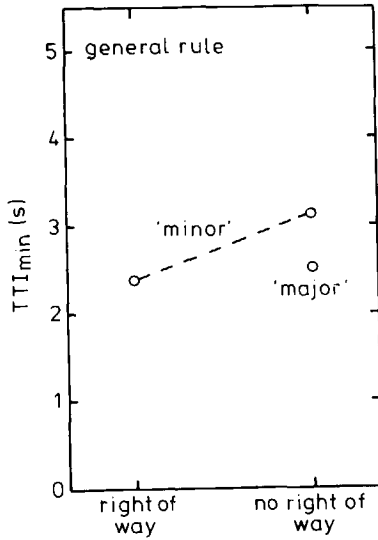


Fig. 5.14 Mean TTI_{\min} for car approaches with a TTI_{\min} at the general rule intersection by right of way and character of the road.

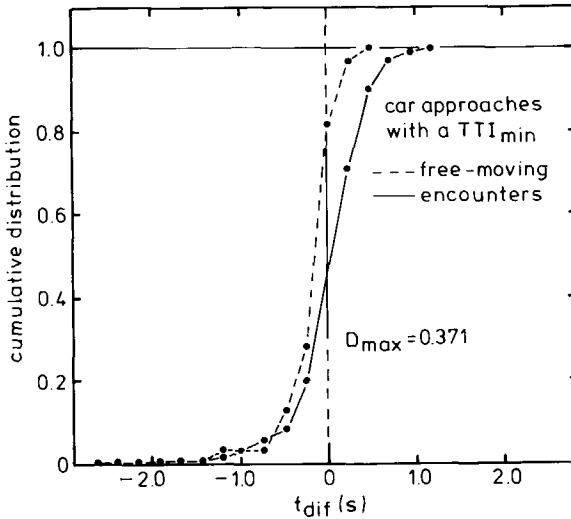


Fig. 5.15 Cumulative distributions of the difference in time between the moment of maximum deceleration (t_{ACCmin}) and of TTI_{\min} ($t_{dif} = t_{ACCmin} - t_{TTImin}$) of free-moving cars and cars involved in an encounter and approaching from the minor road at both intersections.

5.2.3 Time-To-Intersection at moment of first head movement (TTI_{1st})

Similar to the analysis of head movements of free-moving car drivers (Section 4.4.1) the direction of the first head movement is taken as an indicator for the initial priority in directing attention. Fig. 5.16 gives for both types of intersections the percentages of approaches from the minor road where the first head movement is to the right without (free-moving) and with a party on the main road. For the latter group a subdivision is made with regard to the direction the party is coming from.

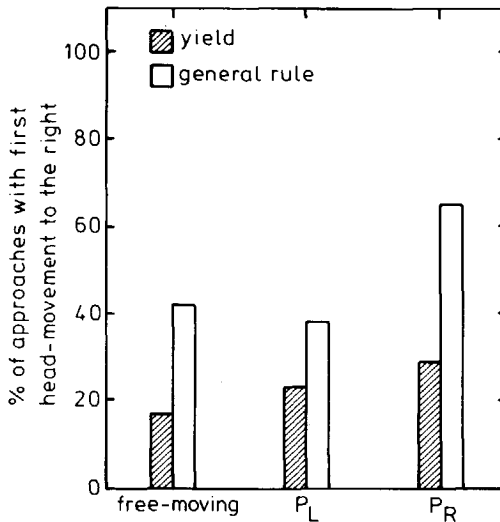


Fig. 5.16 Percentage of car approaches from the minor road with the first head movement to the right without (free-moving) and with a party on the main road (P_L = party from the left, P_R = party from the right) by priority regulation.

At both intersections it does not matter whether the party is a car or a bicyclist. Therefore, the data of both types of encounters are taken together for further analysis. A log-linear model fit reveals that at the general rule intersection the first head movement is more frequently to the right than at the yield intersection ($\chi^2 = 12.42$, $df = 4$, $Q = 0.01$). Adding the type of approach (free-moving, party from the left, or party from the right) also significantly contributes to the model ($\chi^2 = 10.24$, $df = 2$, $Q = 0.006$). A separate log-linear model fit on the data of the yield intersection reveals that neither the direction of the party on the main road (P_L or P_R) nor the type of road user (car or bicyclist) influences the direction of the first head movement. A model with a fixed proportion of approaches with the first head movement to the right of 26% describes the yield intersection data well ($\chi^2 = 3.28$, $df = 3$, $Q = 0.35$). At the general rule intersection, however, the presence of a party

from the right (irrespectively whether the party is a car or a bicyclist) significantly increases the number of first head movements to the right ($\chi^2 = 6.84$, $df = 1$, $Q = 0.009$).

The TTI at the moment the first head movement of car drivers from the minor road is in the direction of the party on the main road has been determined. In Fig. 5.17 the mean values of TTI_{1st} , $DIST_{1st}$, and V_{1st} when the first head movement is to the left (P_L) or to the right (P_R) are contrasted with the values of free-moving cars (Section 4.4.1). No distinction between car-car and car-bicyclist encounters is made since none of the variables significantly differed with respect to the type of party involved. ANOVAs on each of the variables reveal that in an encounter the first head movement is made at the same distance but at a lower speed ($F(1,295) = 5.23$, $p < 0.05$) than for free-moving cars, resulting in a higher TTI_{1st} ($F(1,295) = 12.5$, $p < 0.001$).

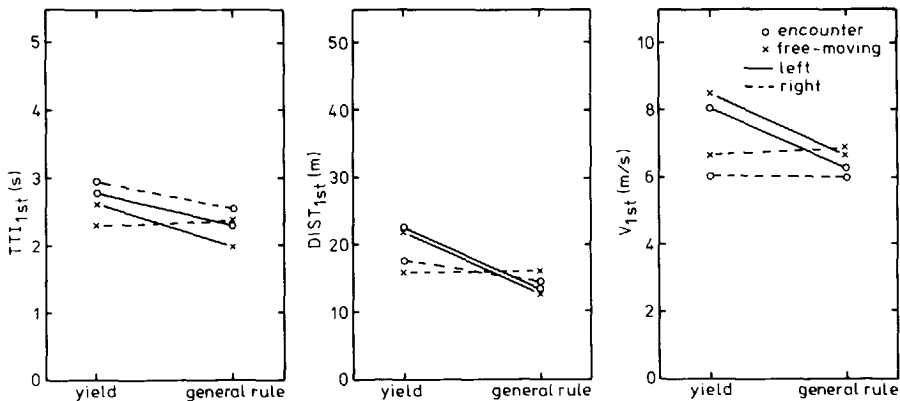


Fig. 5.17 Effects of priority regulation on TTI, DIST, and V at the moment the first head movement is in the direction of the party (left or right).

When the first head movement at the yield intersection is to the left, this head movement occurs at a greater distance ($F(1,295) = 18.8$, $p < 0.001$) and with a higher speed ($F(1,295) = 15.5$, $p < 0.001$) than at the general rule intersection, also resulting in a somewhat higher TTI_{1st} ($F(1,295) = 4.02$, $p < 0.05$). The cars from the minor road involved in an encounter have a lower speed at the moment the first head movement is in the direction of the party than free-moving cars, but due to corresponding distances TTI_{1st} in an encounter is higher.

In encounters between cars from the minor road and parties on the major road coming from the left (P_L) also head movement patterns of P_L parties on the major road (both car drivers and bicyclists) have been analysed. For them, the interacting road user consists of a minor road car approaching from the right. At the yield intersection 31% of the car drivers makes a first head movement in the direction of the approaching car from the minor road, while 63% doesn't display any head movement at all (Fig. 5.18). At the general rule intersection most car drivers look to the right first (83%). The behaviour of bicyclist doesn't differ that much for both types of intersections, nor by the proportions of bicyclists without or with the first head movement in the direction of the party, nor by TTI_{1st} , $DIST_{1st}$, or V_{1st} (Fig. 5.19). At a relatively large TTI value of about 3.6 s bicyclists on the major road start looking to the car from the right, irrespectively of whether they have the right of way or not. The right of way of car drivers on the major road at the yield intersection strongly influences their behaviour. If they make their first head movement in the direction of the minor road car, they do this at a similar distance as at the general rule intersection, but with a much higher speed resulting in a relatively low mean TTI of 1.15 s. Also compared with the moments the first head movement by car drivers from the minor road is in the direction of a car approaching on the major road from the right (the broken lines in Fig. 5.19), this TTI_{1st} is very low. The interaction type of priority regulation x approach direction (major/minor), $F(1,94) = 21.5$, $p < 0.0001$, accounts for 15.3% of explained variance.

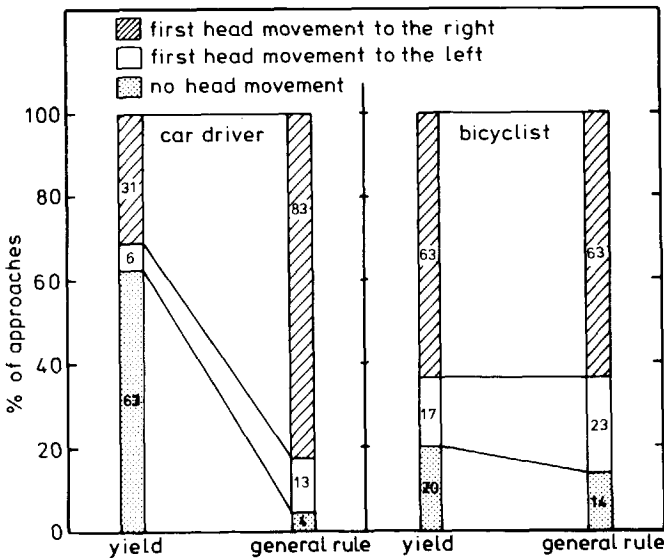


Fig. 5.18 Percentages of both car and bicycle approaches on the major road in an encounter with a minor road car from the right by type of priority regulation.

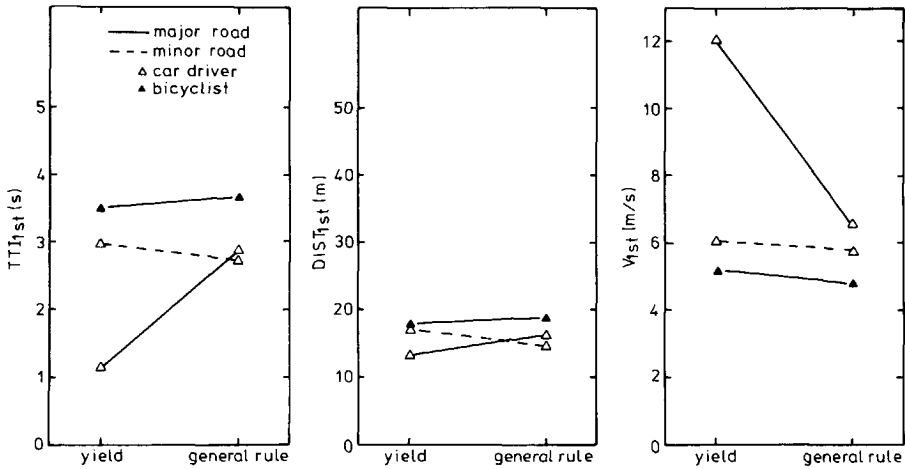


Fig. 5.19 Effects of the right of way for car drivers and bicyclists on the major road over a minor road car coming from the right on TTI, DIST, and V at the moment the first head movement is in the direction of the minor road car. The broken lines represent data of minor road drivers when confronted with a car on the major road coming from the right.

5.3 Time-To-Collision (TTC)

In the previous section the time measure TTI was used to describe road user behaviour at intersections relatively to the entering of the road to be crossed in situations where actually a road user was present at the other road. To analyse the interactions with other road users themselves, the time measure Time-To-Collision (TTC) can be used if a collision course exists. A collision course occurs when two vehicles will meet both in space and in time if they continue their momentaneous speed and heading. In particular, the minimum TTC value (TTC_{min}) indicates how imminent an actual collision has been during the process of approaching each other. In the following subsections the data of several observational studies dealing with interacting behaviour at intersections will be discussed with respect to TTC_{min} . In this context Section 5.3.1 presents the data for the yield and the general rule type of priority regulation for both car-car and car-bicyclist interactions. In Section 5.3.2 the effects of the different types of lay-outs at intersections with separate bicycle tracks on TTC_{min} will be discussed for car-bicyclist interactions, whereas in Section 5.3.3 the results of the two calibration studies on Traffic Conflicts Techniques will be discussed with respect to TTC.

5.3.1 Encounters at yield and general rule intersection

On an average, 58% of the 644 encounters that were analysed quantitatively in the study on the type of priority regulation, had a collision course, and, consequently, for those a TTC curve could be computed and a TTC_{min} determined. The proportion of encounters with a collision course appears to be dependent of the type of priority regulation. At the yield intersection 65% of the encounters had a collision course, whereas at the general rule intersection about 41% had one, Fig. 5.20. From Fig. 5.20 it is also clear that an interaction effect type of priority regulation x type of encounter exists; at the general rule intersection encounters among cars and bicyclists less frequently result in a collision course than at the yield intersection.

The mean TTC_{min} of all encounters having a collision course ($n=373$) at both intersections is 3.05 s with a standard deviation of 1.21 s. Because of the skewness of the distribution of TTC_{min} values, see Fig. 5.21, the median TTC_{min} is lower, viz. 2.64 s. The 15th percentile value is 1.94 s. Six out of 373 encounters display a TTC_{min} less than 1.5 s (1.6%), being only 0.9% of all encounters that were selected ($n=644$).

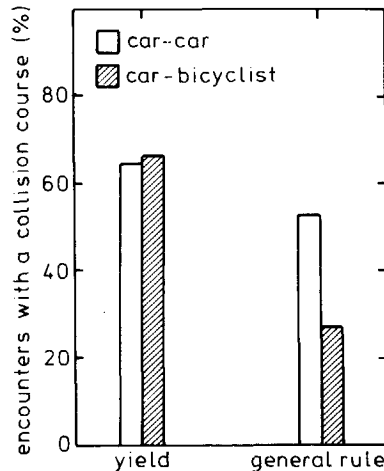


Fig. 5.20 Proportion of encounters with a collision course by type of encounter and of priority regulation.

An ANOVA on TTC_{min} with dimensions type of priority regulation (yield of general rule), direction the party is coming from (left or right), and type of party (car of bicyclist) reveals that there is only a small main effect of the direction the party is coming from ($F(1,365) = 4.15$, $p < 0.05$, 1.7% of explained variance) and a second order interaction effect between regulation, direction, and party ($F(1,365) = 5.22$, $p < 0.05$, 2.3% of explained variance). At the yield intersection there is no significant

difference between car-car and car-bicyclist encounters, whereas encounters with a party coming from the right (second lane on the main road) have a higher TTC_{min} than encounters with parties from the left (mean TTC_{min} 3.33 vs. 2.93 s, median 2.81 vs. 2.53 s, and 15th percentile of 2.09 vs. 1.86 s, respectively). This may be well explained by the additional available space that is available when encountering a road user from the right since the data on both TTI_{br} and TTL_{min} (Section 5.2) indicate that the approaching behaviour by the minor road driver especially is related to the border of the main road itself and not to the direction the party is coming from. At the general rule intersection, however, the influence of the character of the road on which the road user has the right of way appears to be important. Encounters among cars from the minor road and major road cars from the right (having the right of way) have a higher TTC_{min} than encounters among major road cars from the left and cars from the minor road (having the right of way), viz. a mean TTC_{min} of 3.44 vs. 2.74 s, a median of 2.98 vs. 2.53 s, and a 15th percentile value of 2.46 vs. 1.92 s, respectively. Car-bicyclist encounters do not reveal any systematic effects of the direction the bicyclist is coming from.

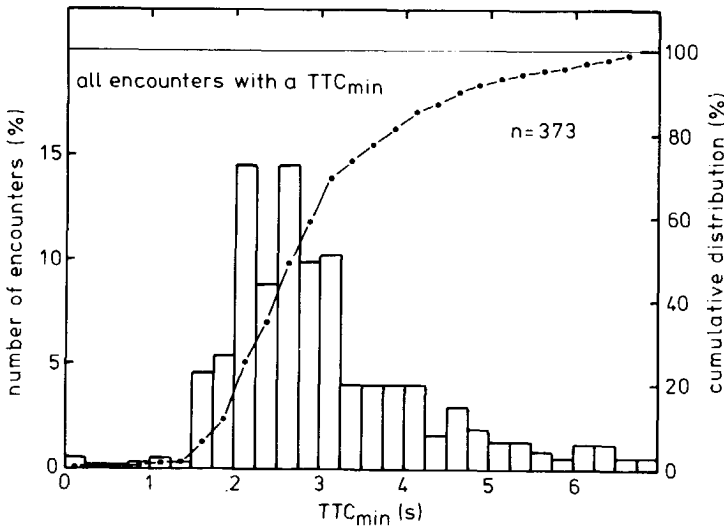


Fig. 5.21 TTC_{min} distribution of all encounters displaying a collision course at both intersections. The scale at right relates to the cumulative distribution.

5.3.2 Encounters at intersections with separate bicycle tracks

In Sections 4.4.2 and 4.4.3 the behaviour of free-moving cars at non-signalised bicycle route intersections was related to intersection lay-out in terms of time related measures. In addition to the analysis of free-moving cars, also a large amount of

interactions among road users at fifteen bicycle route intersections and three control intersections was analysed quantitatively from video, viz. 2336 encounters in total, of which 140 were car-car encounters, 172 bicycle-bicycle or bicycle-moped encounters, 1998 encounters between cars crossing the bicycle track and traffic on the bicycle track (bicycles or mopeds), and 26 remaining encounters that occurred elsewhere at the intersection. In the following the emphasis will be on the car-bicycle(+moped) encounters. On an average, 74% of these encounters had a collision course, and consequently, a TTC curve could be computed. Table XV gives the number of car-bicycle (+moped) encounters by type of location and type of manoeuvre. It was decided to pool the data with respect to bicycles and mopeds at the cycle track (in the following referred to as bicycles), since a first analysis revealed that the TTC_{min} distributions of car-bicycle and car-moped encounters did not differ significantly.

Table XV Number of encounters (n) between cars from and towards the minor road and bicycles (+ mopeds) on the cycle track by type of manoeuvre and type of location; N = number of locations within each group.

direction of crossing	type of location	left turn		straight on		right turn		Total
		N	n	N	n	N	n	
from minor road	The Hague control	8	222	5	174	4	227	623
		3	70	1	15	3	31	116
towards minor road	The Hague control	6	188	3	137	3	73	398
		3	20	1	8	3	59	87
-	Tilburg	2	142	3	565	2	67	774
Total		642		899		457		1998

In Table XVI the 15th percentile, median, and mean values of the TTC_{min} distributions of car-bicycle encounters are given. In general, the distributions are similar for each type of manoeuvre. Fig. 5.22 gives the TTC_{min} distribution of all car-bicycle encounters. In total, 216 encounters (14.6%) had a TTC_{min} of less than 1.5 s. For the comparisons of different intersection lay-outs and/or road design elements no distinction into type of manoeuvre will be made.

Table XVI 15th percentile, median, and mean TTC_{min} values of car-bicycle encounters by type of manoeuvre (all locations and from and towards minor street combined).

type of manoeuvre	n	15 th perc.	median	mean
left turn	436	1.36	2.04	2.50
straight on	730	1.44	2.12	2.44
right turn	311	1.40	2.03	2.54
Total	1477	1.41	2.09	2.48

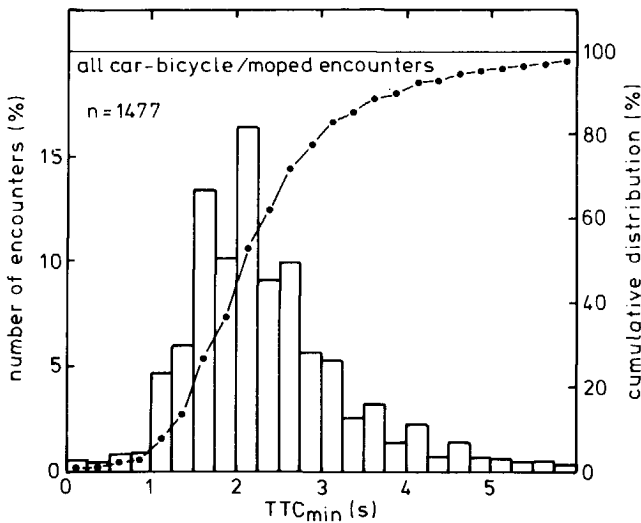


Fig. 5.22 TTC_{min} distribution of all car-bicycle encounters that display a TTC.

At most experimental locations at The Hague the cycle track has bicycle traffic in two directions and is located at one side of the main road. The bicycle stream that is intersected first by traffic from the minor road is referred to as B_1 , whereas the bicycle stream into the other direction (contra stream) is indicated by B_2 . Four experimental locations at The Hague (H1-H4) can be compared with the three control locations with respect to encounters between intersecting cars both from (car_f) and towards (car_T) the minor street and bicyclists of stream B_1 . In general, at the experimental locations bicyclists on the cycle track experience higher TTC_{min} values in encounters with cars crossing the cycle track than at the control locations

(Kolmogorov-Smirnov test, $D_{\max} = 0.178$, $p < 0.025$), see Fig. 5.23. At the experimental locations the 15th percentile, median, and mean TTC_{\min} are higher, viz. 1.44, 2.05, and 2.51 s vs. 1.16, 1.85, and 2.27 s, respectively.

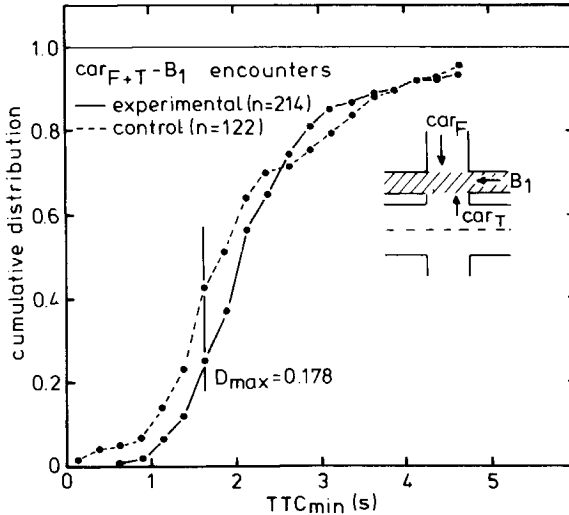


Fig. 5.23 TTC_{\min} distributions of encounters between cars from and towards minor road and stream B_1 road users at experimental and control locations.

At the experimental locations at The Hague the TTC_{\min} distributions of car-bicycle encounters appear to be dependent of the approach direction of the bicyclist involved. The bicycle stream that is crossed first experiences encounters with lower TTC_{\min} values than the second bicycle stream to be crossed. As an example, Fig. 5.24 gives the TTC_{\min} distributions of $car_F - B_1$ and $car_F - B_2$ encounters, but the same holds for encounters with intersecting cars towards the minor street.

At the experimental locations at Tilburg, where cars only have to negotiate the cycle track, no systematic effect of the direction the bicyclist is coming from, appears to be present.

For the experimental locations at The Hague it was tested whether the direction from which the intersecting cars approach the cycle track (from or towards minor road) has an effect on the TTC_{\min} distribution. Encounters between road users on the cycle track and cars towards the minor road have higher TTC_{\min} values than encoun-

ters with cars from the minor road (Kolmogorov-Smirnov test, $D_{\max} = 0.202$, $p < 0.001$), Fig. 5.25. The 15th percentile values, however, do not differ very much.

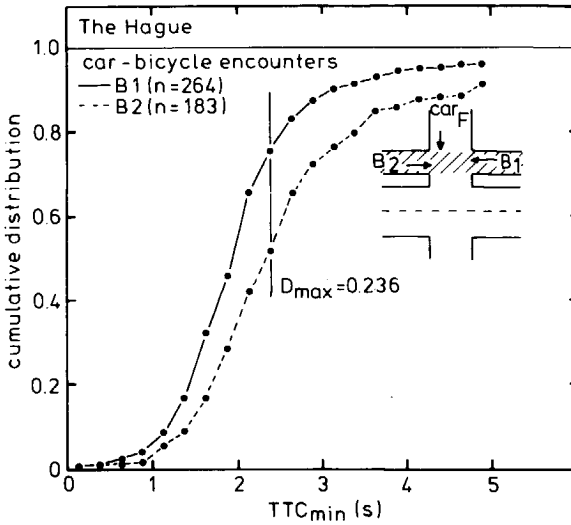


Fig. 5.24 TTC_{\min} distributions of encounters between cars from the minor road and road users of both bicycle streams at the cycle track of experimental locations at The Hague.

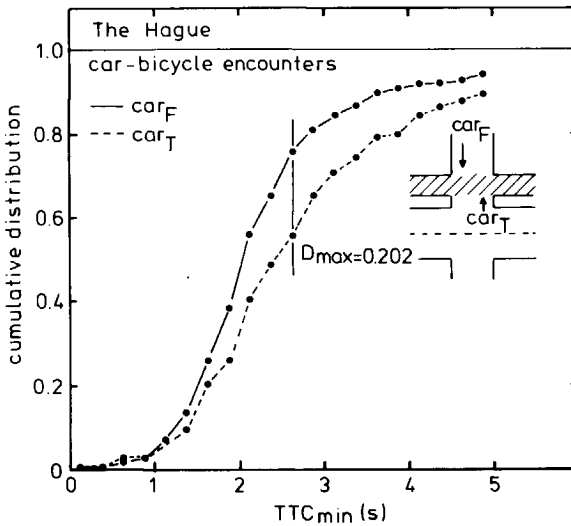


Fig. 5.25 TTC_{\min} distributions of encounters between road users on the cycle track and cars from (car_F) or towards (car_T) minor road at the experimental locations at The Hague.

Some specific effects of different intersection design elements, such as the short and long median at location T1, the differences in priority regulation, intersection sight distance, and shape of speed control humps at the locations T3 and T5 (see Section 4.4.3), and speed control humps at a distance of about 5 m to (location H1) or bordering the cycle track (location H3), are summarised in Table XVII.

Table XVII Specific effects of some intersection design elements on TTC_{min} distributions; short vs. long median at location T1; i.a. yield sign at location T3 vs. stop sign at location T5, and speed control humps at a distance of about 5 m to the cycle track at location H1 vs. hump bordering the cycle track at location H3 (n = number of encounters with a TTC_{min}).

location	measure	n	15 th perc.	median	mean	D_{max}	p^*
T1	short median	73	1.12	1.62	1.88	0.455	<0.001
	long median	56	1.82	2.38	2.75		
T3	i.a. yield	156	1.74	2.33	2.55	-0.235	<0.001
T5	i.a. stop	229	1.42	1.99	2.22		
H1	humps at 5 m	164	1.67	2.31	2.75	-0.202	<0.005
H3	humps at 0 m	192	1.35	2.03	2.65		

* Kolmogorov-Smirnov test, two-tailed.

5.3.3 Encounters of the calibration studies on Traffic Conflicts Techniques

Under the auspices of the ICTCT two international studies on calibrating Traffic Conflicts Techniques have been conducted. The Malmö study relates to the observation of three urban intersections and is briefly described in Section 3.4.5; the Trautenfels study deals with the observation of a rural intersection, see Section 3.4.6.

From the Malmö study three subsets of data are available for the evaluation of the TTC measure, viz.:

- 1) subset 1, the subset of 111 conflicts scored by four or more observer teams in the field together with six other conflicts scored by less teams but with a high severity score, in total 117 conflicts,
- 2) subset 2, consisting of all the conflicts scored by at least one team during one day at the intersection with right-hand general rule priority (day 7), except for two

conflicts that could not be found on video tape (total of the subset 120 conflicts), and

- 3) subset 3, the video selection of encounters on day 7 with a close proximity between the road users involved, but not scored by one of the observer teams in the field, resulting in 100 encounters (the criterion for close proximity was a roughly estimated minimum TTC of about 1.5 s or less).

From the Trautenfels study 122 conflicts could be analysed quantitatively from video (see Section 3.4.6). A considerable number of these conflicts (49 conflicts in all) can be characterised as typical PET situations, mostly consisting of left turning cars in front of oncoming traffic. For the evaluation of the TTC measure these conflicts were not included. So, 73 conflicts remain for further analysis.

Table XVIII gives a subdivision of all the conflicts from the Malmö study as observed by the teams in the field and of the conflicts in the subsets 1 and 2 into the number of teams that scored a given conflict. Subset 1 represents 12% of all 974 conflicts. The overlap between subset 1 and 2 consists of 14 conflicts in total.

Table XVIII Number of all conflicts observed in the Malmö study and of the conflicts in subset 1 and 2, subdivided by the number of teams that scored a given conflict.

	total	1	2	3	4	5	6	7	8 teams
total set	974	604	162	97	42	27	20	13	9
subset 1	117	-	4	2	42	27	20	13	9
subset 2	120	74	24	11	2	5	2	1	1

Table XIX gives the number of conflicts/encounters in each subset by type of road users involved. Subsets 1 and 2 are comparable with respect to the type of conflicts, whereas the extra selection from video (subset 3) contains relatively less car-car encounters and more car-pedestrian and bicyclist-bicyclist or bicyclist-pedestrian encounters than the conflicts observed by the teams in the field. From the 117 conflicts of subset 1, 36 conflicts occurred at the low speed general rule intersection, 60 at the high speed yield intersection, and 21 at the signalised intersection. In total, 101 conflicts from subset 1 display a TTC (86.3%). Fig. 5.26 gives the TTC_{min} distributions at the three Malmö intersections, together with the TTC_{min} distribution

of the TTC conflicts from the Trautenfels study. No systematic differences among the three Malmö intersections are present. On an average, the 15th percentile value is only 0.57 s, the median TTC_{min} 1.52 s, and the mean TTC_{min} is 1.53 s. The TTC_{min} distribution of the conflicts at the Trautenfels intersection (15th percentile TTC_{min} = 0.73 s, median 1.58 s, and mean 1.72 s) does not significantly differ from the others either.

Table XIX Number of conflicts/encounters in the three subsets by type of road user involved; the category 'car' also includes lorries or buses, 'other' consists of bicyclist-bicyclist or bicyclist-pedestrian interactions.

	subset 1	subset 2	subset 3
car - car	69	62	32
car - bicyclist	25	27	21
car - pedestrian	18	22	32
other	5	9	15
total	117	120	100

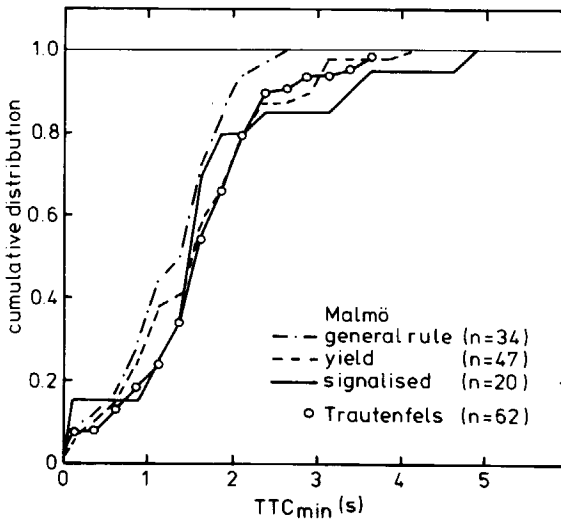


Fig. 5.26 TTC_{min} distributions of the conflicts from Malmö subset 1, subdivided by type of intersection, and from the Trautenfels study.

The further analyses in this section refer to the data of the Malmö study only.

The type of conflict, viz. car-car, car-bicyclist, or car-pedestrian does not largely effect the TTC_{min} distributions either (Fig. 5.27), although the conflicts of cars with bicyclists or pedestrians relatively frequently tend to have very low TTC_{min} values compared with car-car conflicts (15th percentile TTC_{min} of 0.25 s vs. 0.80 s). All median TTC_{min} values, however, are close to 1.5 s again.

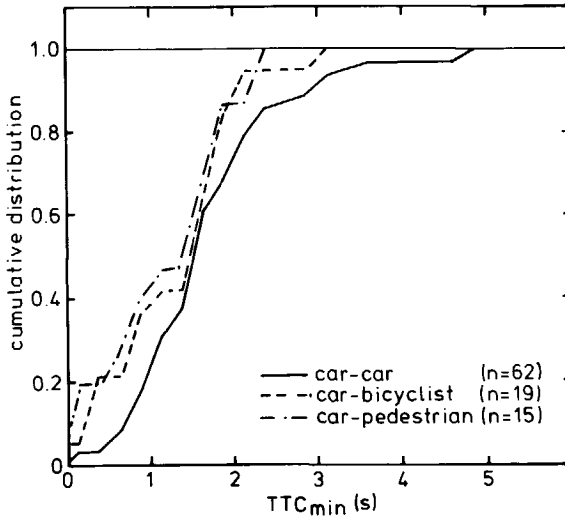


Fig. 5.27 TTC_{min} distributions of the conflicts from subset 1 by type of road user involved.

In general, the conflicts that were scored by less than four teams (mainly from subset 2 at the general rule intersection) have a higher TTC_{min} than the conflicts that were scored by at least four teams (subset 1), see Fig. 5.28 (Kolmogorov-Smirnov test, $D_{max} = 0.268$, $p < 0.005$).

The TTC_{min} distribution of the from video selected encounters with a close proximity between the road users involved (subset 3) does not significantly differ from the distribution of the encounters scored by one team or more (subset 2), see Fig. 5.29; the 15th percentiles TTC_{min} are 0.65 and 0.74 s, respectively, and the median values 1.52 and 1.63 s. So, based on a TTC conflict definition a considerable amount of these encounters should have been regarded as conflicts. Unknown is whether these situations were not detected by the observer teams in the field at all, or that they were observed indeed, but not regarded to be serious enough for registration. Both

arguments may be applicable to the encounters in subset 3 since subset 3 contains relatively many car-pedestrian and 'other' encounters compared with the conflicts observed by the teams in the field (subset 2), Table XIX.

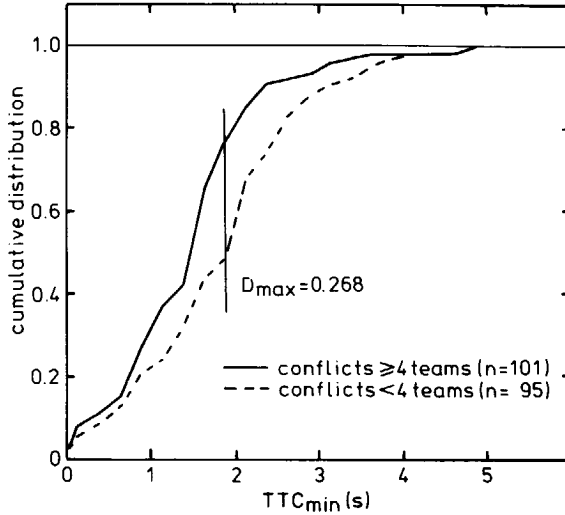


Fig. 5.28 The TTC_{min} distribution of conflicts scored by less than four teams compared with that of the conflicts scored by four teams or more.

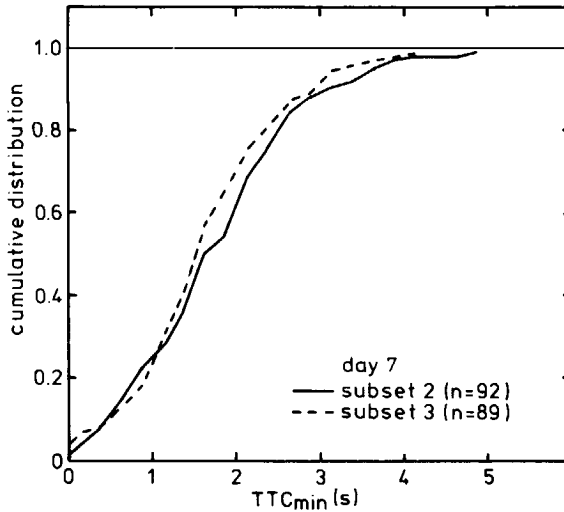


Fig. 5.29 TTC_{min} distributions of the conflicts scored in the field on day 7 (subset 2) and of the encounters selected from video in addition (subset 3).

On the one hand, those encounters may be more difficult to detect, on the other the TTC criterion value for scoring those interactions as a conflict may be lower than for example for car-car encounters. But when comparing the TTC_{min} distributions of car-car encounters in both subsets, subset 3 even tend to have lower TTC values than subset 2 ($t = 1.90$, $df = 84$, $p < 0.1$). A further examination of subset 2, however, reveals that the conflicts scored by only one team have significantly higher TTC_{min} values than the conflicts scored by more than one team (Kolmogorov-Smirnov test, $D_{max} = 0.39$, $p < 0.001$), Fig. 5.30. They also have higher TTC_{min} than the encounters of subset 3 (Kolmogorov-Smirnov test, $D_{max} = 0.263$, $p < 0.025$).

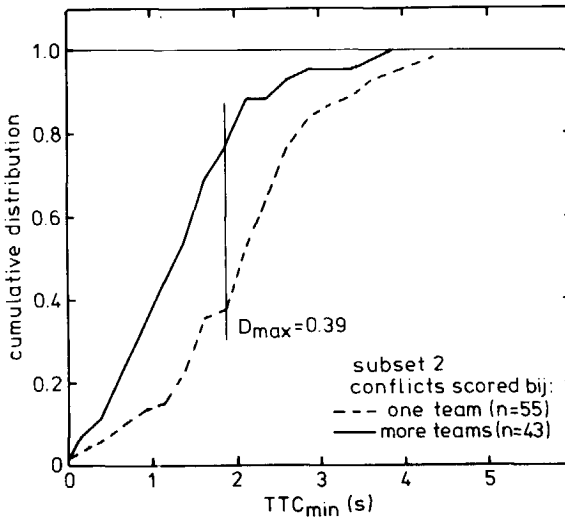


Fig. 5.30 Cumulative TTC_{min} distributions of conflicts from subset 2 scored by one team and of those scored by more than one team.

5.4 Post-Encroachment-Time (PET)

As discussed in Section 3.3.2 the Post-Encroachment-Time (PET) may be helpful in defining certain types of conflicts, viz. those where road users come into a very close proximity to each other without actually displaying a collision course. To evaluate the PET measure the data of both the Malmö and the Trautenfels calibration study are used. From the Malmö study the same subsets are available as described in Section 5.3.3. Table XX gives the number of conflicts/encounters with a PET for each subset by type of road users involved. On an average, for 37% of the conflicts from subset 1 a meaningful PET could not be computed, mostly because one of the road users involved came to a full stop. Also for rear-end situations the PET measure is not

very suitable. At the signalised intersection the percentage of conflicts with a PET is the highest (76%), at the low speed general rule intersection the lowest (53%).

Table XX Number of conflicts/encounters with a PET in the three subsets of the Malmö data by type of road user involved.

	subset 1	subset 2	subset 3
car - car	41	27	16
car - bicyclist	20	19	17
car - pedestrian	9	14	23
other	4	7	15
total	74	67	71

From the 122 conflicts that could be analysed quantitatively in the Trautenfels study (see Section 3.4.6), 49 conflicts can be characterised as typical PET situations, for the major part consisting of cars that turn left in front of an oncoming car.

Fig. 5.31 gives the cumulative PET distributions of the conflicts from the three subsets of the Malmö data and from the Trautenfels study. The PET distributions of the three subsets from the Malmö study do not differ significantly from each other. On an average, the 15th percentile value is 0.39 s, and the median PET 0.81 s. The conflicts as observed at the rural intersection (Trautenfels) display larger PET values than the conflicts at the urban intersections of the Malmö study (15th percentile PET = 0.52 s, median PET = 1.39 s, and mean PET = 1.43 s).

Within subset 1, the type of intersection does not have a systematic effect on PET (Fig. 5.32a). Car-bicycle conflicts seem to have somewhat lower PET values than car-car or car-pedestrian conflicts (Fig. 5.32b), but the numbers are too small for a statistical proof. Most bicycle-bicycle and bicycle-pedestrian interactions (category 'other') have a rather low PET, for all subsets together the median PET is about 0.4 s.

Similar to the analysis of TTC_{min} , the conflicts that were scored by only one team within subset 2 have considerable higher PET's than the conflicts scored by more than one team, Fig. 5.33 (Kolmogorov-Smirnov test, $D_{max} = 0.385$, $p < 0.05$). The median PET differs about 0.4 s.

Encounters with and without a TTC_{min} do not significantly differ with respect to their PET distributions for either one of the subsets.

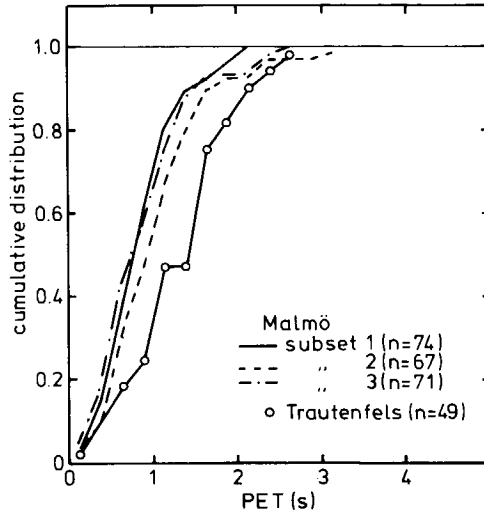


Fig. 5.31 PET distributions of the conflicts from the Malmö subsets and of the conflicts from the Trautenfels study.

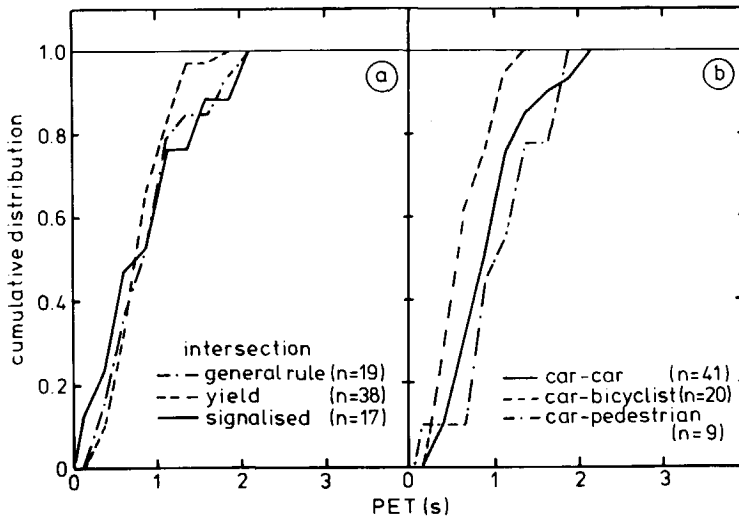


Fig. 5.32 PET distributions of the conflicts from subset 1 by type of intersection (Fig. 5.32a) and by type of conflict (Fig. 5.32b).

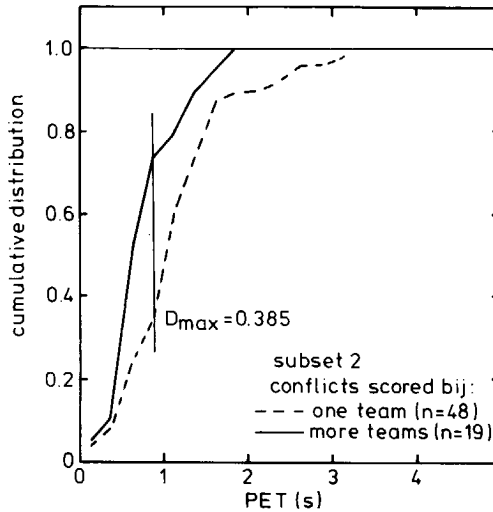


Fig. 5.33 Cumulative PET distributions of conflicts from subset 2 scored by one team and of those scored by more than one team.

5.5 Comparison between objective measures and subjective scores

So far, interactions between road users have been described by objective measures as obtained from an off-line quantitative analysis of video recordings. From the two calibration studies on Traffic Conflicts Techniques, viz. both the Malmö and the Trautenfels study (see Section 3.4.5 and 3.4.6, respectively), also data are available on severity scores of traffic conflicts by several observer teams in the field. In the Malmö study observer teams from eight countries simultaneously made traffic conflicts registrations at three intersections, each team according to its own definition and operational procedure. In the Trautenfels study six traffic conflicts observation teams participated. For both studies the Institute for Road Safety Research SWOV conducted a homogeneity analysis on the traffic conflicts severity scores of the observer teams in the field with the help of the programme PRINCALS (principal components analysis of categorical data), Oppe [1982]; Grayson (Ed) [1984]; Oppe [1986]. This analyses revealed that there are considerable differences in scoring among the teams but that these mainly result from differences in the detection of relevant situations. Once a situation is detected, however, there exists a rather good agreement among the teams. The severity scores of all teams can be represented well by a one-dimensional severity scale. On an average, conflicts are scaled on this dimension in the right order by all teams. In the one-dimensional solution of

PRINCALS each conflict gets one severity score on this common dimension. This enables a direct comparison of measures such as TTC or PET with the PRINCALS scores as a good representative of the subjective scores by the observer teams. For the Malmö data two different PRINCALS scores will be used, viz. DIM1 that results from an analysis of severity scores of subset 1 (see Section 5.3.3) only, and DIM2 that is based on an analysis of the total set of conflicts. Therefore, for each conflict in subset 1 both severity scores DIM1 and DIM2 are available. Both scores are highly correlated with $r = 0.89$, $p < 0.0001$. For the conflicts of subset 2 only the severity dimension DIM2 is available. The PRINCALS score of the conflicts from the Trautenfels study will be referred to as DIM3. In the comparison between objective measures and the severity dimensions given, use is made of one or more of the objective variables as listed in Table XXI.

Table XXI List of objective measures, as employed in the comparison with the severity dimensions DIM1, DIM2, and DIM3. Road user 1 refers to the road user with the formal right of way, road user 2 to the other road user involved in the interaction.

V1	Initial speed of road user 1 in m/s.
V2	Initial speed of road user 2 in m/s.
ACC1 _{min}	Highest level of acceleration or deceleration (m/s ²) of road user 1 as occurring around the minimum temporal proximity between the road users.
ACC2 _{min}	Idem for road user 2.
MDIS	Minimum distance between road users involved (m), as measured between the two nearest points of both road users before, during, or after the interaction.
TTC _{min}	Minimum value (s) of the Time-To-Collision (TTC) measure that is based on a constancy of speed and heading angle (see Section 3.3.1).
DTTC	Distance between both road users at the moment TTC _{min} occurs (m).
TTCA _{min}	Minimum value (s) of the Time-To-Collision (TTCA) measure that is based on a constancy of acceleration and heading angle.
DTTCA	Distance between road users at the moment TTCA _{min} occurs (m).
TTC1 _{br}	TTC at the onset of braking (or accelerating) by road user 1, defined as the moment the deceleration or acceleration exceeds a level of 0.5 m/s ² preceding the moment TTC _{min} occurs.
TTC2 _{br}	Idem for road user 2.
PET	Post-Encroachment-Time (s) (see Section 3.3.2).

Compared with the set of objective variables that were used for the non-metric canonical correlation analysis (CANALS) as reported by Grayson (Ed) [1984], three TTC variables are added, viz. TTCA_{min}, TTC1_{br}, and TTC2_{br}. Therefore, the emphasis of this analysis will be on a comparison of the different TTC measures in relation-

ship to the severity dimensions. Since the PET measure deals with very specific situations that are more or less complementary to situations with a collision course, the PET measure is treated separately.

5.5.1 Conflicts of subset 1 from the Malmö study

First of all, subset 1 is used to compare the objective measures (with the exception of PET) with the severity dimensions DIM1 and DIM2. $TTC_{1_{br}}$ and $TTC_{2_{br}}$ values were only available for a restricted number of conflicts, either because the deceleration did not exceed the 0.5 m/s^2 level or because this level already was exceeded at the entrance of the video scene. Therefore, four sets of variables were used, viz. one without $TTC_{1_{br}}$ and $TTC_{2_{br}}$, one with $TTC_{1_{br}}$ only, one with $TTC_{2_{br}}$, and one with both included. Table XXII gives the results of multiple regression analyses with DIM1 and DIM2 as the dependent variable, respectively.

Table XXII Correlation coefficients of the variables included in the equation of a multiple regression analysis on the objective and subjective data of subset 1 from the Malmö study and the partial correlation coefficients of the variables that not significantly contribute (n is the number of conflicts, x = given variable excluded from analysis).

		DIM1				DIM2				
		n	96	56	55	38	96	56	55	38
included	TTC_{min}		-0.46	-0.49	-0.50	-0.44	-0.42	-0.47	-0.47	-0.43
	V2					-0.29				
multiple r			.46	.49	.50	.54	.42	.47	.47	.43
not included	V1		-0.01	.07	.07	.09	.02	.09	.11	.28
	V2		-0.05	-0.15	-0.22	.03	.00	-0.14	-0.27	
	$ACC_{1_{min}}$.08	-0.06	.07	-0.14	-0.01	-0.06	-0.02	-0.27
	$ACC_{2_{min}}$.02	.13	-0.03	-0.19	-0.04	.06	-0.14	-0.01
	MDIS		-0.04	.23	.03	.15	-0.06	.19	.03	.08
	$TTCA_{min}$		-0.06	-0.03	-0.05	-0.07	-0.01	.03	.04	-0.02
	$TTC_{1_{br}}$		x	.05	x	.02	x	.09	x	.06
$TTC_{2_{br}}$		x	x	-0.17	.08	x	x	-0.12	-0.11	

As is obvious from these results, TTC_{min} correlates highest with DIM1 and DIM2 for all sets (all correlations of TTC_{min} are significant at the $p < 0.0005$ level), whereas the other TTC measures do not significantly contribute. This does not necessarily

imply that they don't have any relation with the severity dimensions DIM1 or DIM2. But because they all correlate with TTC_{min} ($TTCA_{min}$, $r = 0.81$, $p < 0.0001$; $TTC1_{br}$, $r = 0.45$, $p < 0005$; $TTC2_{br}$, $r = 0.55$, $p < 0001$), their contribution is low once TTC_{min} is included in the regression equation. From Table XXIII, that gives the univariate correlation coefficients of each objective variable with DIM1 and DIM2, respectively, it appears that from the TTC measures, $TTC1_{br}$ does not significantly correlate with one of the severity dimensions DIM1 or DIM2. Both $TTCA_{min}$ and $TTC2_{br}$, however, are significantly correlated with DIM1 and DIM2, but TTC_{min} still scores the highest.

Table XXIII Univariate correlation coefficients of the objective variables with the subjective severity dimensions DIM1 and DIM2 for subset 1 of the Malmö study (n = number of conflicts with given variable available; n.s. = not significant at the $p < 0.05$ level).

	n	DIM1		DIM2	
		r	p	r	p
V1	116	-.16	n.s.	-.15	n.s.
V2	116	.05	n.s.	.11	n.s.
$ACC1_{min}$	100	.04	n.s.	-.03	n.s.
$ACC2_{min}$	100	-.07	n.s.	-.11	n.s.
MDIS	116	-.31	0.001	-.29	0.002
TTC_{min}	100	-.48	0.001	-.43	0.001
$TTCA_{min}$	98	-.39	0.001	-.33	0.001
$TTC1_{br}$	57	-.18	n.s.	-.14	n.s.
$TTC2_{br}$	57	-.40	0.002	-.34	0.01
PET	73	-.37	0.002	-.27	0.02

Although TTC_{min} has the highest correlation with both subjective severity dimensions, the correlation coefficient itself is rather low. To be able to make comparisons with data from subset 2 and because both severity dimensions give similar results, we will concentrate on severity dimension DIM2. The scatterdiagram of TTC_{min} with DIM2 from Fig. 5.34 shows that conflicts with a high severity score have relatively low TTC_{min} values, but that not all conflicts with low TTC_{min} values are regarded as very severe conflicts. But with a median value of 0.95 for DIM2, it is also clear from Fig. 5.34 that even subset 1 (mainly consisting of conflicts scored by four or more teams) contains many relatively slight conflicts.

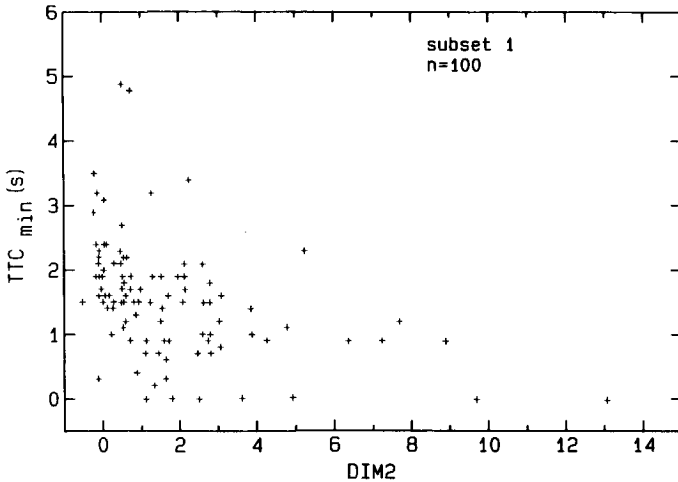


Fig. 5.34 Scatterdiagram of TTC_{min} with severity dimension DIM2 for subset 1 from the Malmö study.

A multiple discriminant analysis was performed between two groups of conflicts, viz. one consisting of the conflicts with a DIM2 value below the median and the other of the conflicts with a DIM2 above the median of DIM2 to investigate which variables discriminate between both groups. From the set of variables that were included (see Table XXIV), again TTC_{min} best separates both groups of conflicts in an univariate comparison, see first column of Table XXIV, but also in the multiple discriminant analysis (Wilks' Lambda parameter is 0.774, $F(9,88) = 2.85$, $p < 0.005$) the canonical loading of TTC_{min} is the highest. Neither speed nor deceleration contributes very much.

From subset 1, 73 conflicts have a PET value. As is to be expected, PET is negatively correlated with the severity dimensions DIM1 and DIM2, see Table XXIII. A multiple regression analysis on the conflicts that have both a PET and a TTC_{min} (56 conflicts), with DIM1 as the dependent variable reveals an about equal influence of PET and TTC_{min} with both variables included (both partial correlations are -0.23, $p < 0.14$, multiple $r = 0.40$). Removal of the variable TTC_{min} increases the influence of PET ($r = -0.27$), whereas a similar effect occurs if PET is removed (TTC_{min} alone gives an r of -0.35), but all together the correlation remains rather low. A multiple regression analysis with DIM2 as the dependent variable, reveals a significant correlation of TTC_{min} ($r = -0.30$), but a combination of both $ACC1_{min}$ ($r = -0.26$) and

PET ($r = -0.27$) also reveals significant correlations ($p < 0.05$). PET and TTC_{min} seem to be complementary to each other, as could be expected.

Table XXIV Results of multiple discriminant analysis between the group of the conflicts from subset 1 with $DIM2 < 0.95$ (median $DIM2$ value) and the one with $DIM2 \geq 0.95$ (n.s. = not significant at the $p < 0.10$ level).

	Univariate F-tests F(1,96)	p	Canonical loadings
V1	0.96	n.s.	0.18
V2	0.03	n.s.	0.03
$ACC1_{min}$	0.62	n.s.	0.15
$ACC2_{min}$	0.01	n.s.	0.02
MDIS	5.44	0.02	0.44
TTC_{min}	22.86	0.00	0.90
DTTC	10.96	0.01	0.63
$TTCA_{min}$	14.81	0.00	0.73
DTTCA	11.97	0.01	0.65

5.5.2 Conflicts of subset 2 from the Malmö study

Subset 2 consists of all the conflicts that were scored by at least one of the teams during day 7 of the Malmö study. On an average, the subjective scores of the conflicts from subset 2 are less severe than those of the conflicts from subset 1; the mean $DIM2$ of subset 2 (-0.06) is significantly lower than the mean of subset 1 (1.68) (t-test, $t = 8.31$, $p < 0.001$). From subset 2, 74 conflicts (62%) were scored by only one team. Compared with the conflicts in subset 2 that were scored by more than one team (mean $DIM2 = 0.36$, s.d. = 0.99), these conflicts are regarded as less severe (mean $DIM2 = -0.32$, s.d. = 0.09), t-test, $t = 5.82$, $p < 0.001$. In Section 5.3.3 it was shown that these conflicts also have higher TTC_{min} values than the conflicts scored by more than one team.

The scatterdiagram of Fig. 5.35 illustrates that the major part of the conflicts scored by only one team has the lowest severity score combined with for the greater part relatively high TTC_{min} values. This suggests that the group of conflicts scored by one team contains a relatively high number of 'false alarms' on the border line between slight conflicts and encounters. Because of the small range of $DIM2$ values in subset 2, a regression analysis is not very feasible.

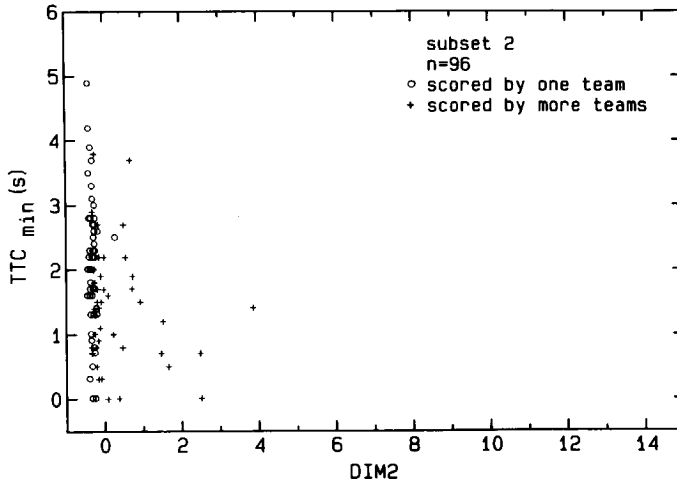


Fig. 5.35 Scatterdiagram of TTC_{min} with severity dimension DIM2 for subset 2 of Malmö study, subdivided by conflicts scored by one team and those scored by more than one team.

5.5.3 Conflicts from the Trautenfels study

A considerable number of the conflicts from the Trautenfels study can be characterised as typical PET conflicts (49 out of the 122 conflicts that were analysed quantitatively from video), mostly consisting of left turning motor vehicles in front of oncoming traffic. This signalised rural intersection fits the circumstances for which the PET measure originally was intended for. But also at this location, the majority of the remaining conflicts (70 out of 73) didn't have an appropriate PET; 43 conflicts were of the rear end type and in the remaining conflicts one of the vehicles involved came to a complete stop. Therefore, the conflicts from the Trautenfels study are subdivided into two separate groups, one consisting of 73 TTC conflicts and the other of 52 PET conflicts. A small overlap of 3 conflicts between both groups is present since these had both low TTC_{min} and low PET values.

The results of a multiple regression analysis on the TTC conflicts group with the subjective severity dimension DIM3 as the dependent variable and V1, V2, $ACC1_{min}$, $ACC2_{min}$, MDIS, TTC_{min} , and DTTC as the independent variables are given in the first column of Table XXV, whereas the results of the PET conflicts with PET included in the set of independent variables is given in the second column.

Table XXV Correlation coefficients of the objective variables included in the equation of a multiple regression analysis with the subjective severity dimension DIM3 as the dependent variable, as well as the partial correlation coefficients of the variables that not significantly contribute. The column at left refers to the set of TTC conflicts of the Trautenfels study, the column at right to the PET conflicts (x = variable is not included in analysis).

		TTC conflicts	PET conflicts
included	TTC _{min}	-.35	
	PET	x	-.27
	V1		.29
	multiple r	.35	.37
not included	V1	.17	
	V2	.12	.03
	ACC1 _{min}	-.23	-.03
	ACC2 _{min}	-.05	-.01
	MDIS	.02	-.08
	TTC _{min}		.15
	DTTC	.00	.00

For the TTC conflicts, only TTC_{min} correlates significantly with DIM3 ($p < 0.01$), but again, the correlation coefficient itself is rather low. For the PET conflicts, both PET and V1 correlate with DIM3 ($p < 0.05$), but the multiple regression coefficient of 0.37 is also rather low. The combination of PET and V1 itself with the given signs of the correlation coefficients seems logical when a situation with a given PET and a high speed of the oncoming car is regarded as more severe than a situation with the same PET but with a low speed of the oncoming car. The scatterdiagrams of Fig. 5.36 illustrate that also the Trautenfels data contain relatively many slight conflicts and only a few severe conflicts; the 85th percentile of the DIM3 distribution of 0.10 covers only 9% of the total range of DIM3 values (from -.56 to 6.81). Moreover, most conflicts with a relatively high TTC_{min} or a high PET value were scored by only one team. For the TTC conflicts from the Trautenfels study a similar pattern occurs as for the conflicts from the Malmö study; severe conflicts have a low TTC_{min}, but not all conflicts with a low TTC_{min} are regarded as severe. In general, the PET conflicts display a similar pattern, but on an average, the PET values of the Trautenfels conflicts are higher than those of the conflicts from the Malmö subset 1, viz. a mean PET of 1.43 s and 0.92 s, respectively (t-test, $t = 4.72$, $p < 0.001$). For the Trautenfels conflicts, the approach speed of the road user that has the right of way

(mean $V1 = 10.3$ m/s, s.d. = 6.2 m/s) does not significantly differ from $V1$ for the conflicts with a PET from the Malmö subset 1 (mean $V1 = 9.0$ m/s, s.d. = 5.5 m/s).

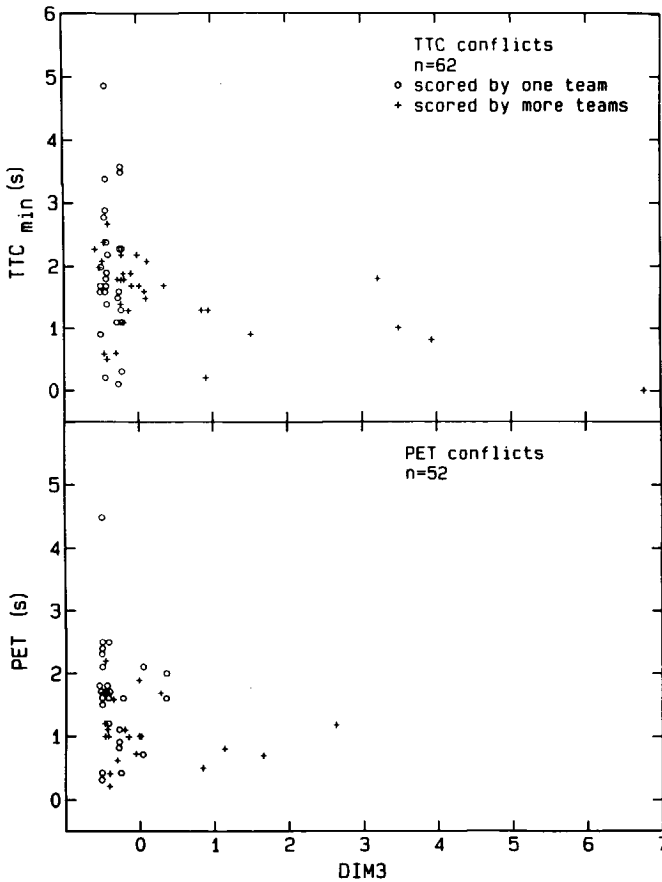


Fig. 5.36 Scatterdiagrams of TTC_{min} (top) and PET (bottom) with the subjective severity dimension DIM for the conflicts from the Trautenfels study, subdivided by conflicts scored by one team and those scored by more teams.

5.6 Discussion and conclusions

The main topic of this chapter was the analysis of road user behaviour in encounters with other traffic. To investigate how road users deal with other road users, and in particular, which time frame applies in normal and critical encounters, three time measures were examined in more detail, viz. Time-To-Intersection (TTI), Time-To-Collision (TTC), and Post-Encroachment-Time (PET). The TTI measure is related to the road itself and enables a direct comparison with the approaching behaviour of free-moving cars, TTC directly relates to the other road user and describes interacting behaviour during the approach process in case of a collision course (assuming a continuation of the momentaneous speeds and heading angles, the road users will collide), whereas PET gives the time margin between the road users that has left in the final stage of an encounter.

Time-To-Intersection

In Chapter 4 it was demonstrated that an analysis of drivers' behaviour in approaching several types of intersections in terms of the TTI measure gives rather consistent results. The same applies for the analysis of approaching an intersection in an encounter with another road user. At a yield intersection, for example, car drivers from the minor road, start braking (defined as the moment the deceleration level exceeds a value of -1 m/s^2) at a rather constant TTI of about 3 s away from the intersection, independently of the type of manoeuvre, type of party on the main road, or the direction the party is coming from. Compared with the onset of braking of free-moving cars, in an encounter braking starts a little bit earlier (about 0.2 s further away from the intersection). TTI_{br} appears to be also rather constant over speed. As can be expected, car drivers on the main road do not very often decelerate in an encounter with a car on the minor road, but if they do, they start braking about 1 s closer to the intersection.

Once the decision to decelerate is made, the control of braking appears to be also consistently conducted. The occurrence of a minimum TTI before actually entering the intersecting road indicates that the driver has enough time available to come to a successful stop, if necessary. At both the yield and the general rule intersection, this type of behaviour is more frequently displayed in an encounter than in an approach without other traffic. At the yield intersection, left turning and straight on going cars from the minor road display this type of behaviour in 75% of the approaches, regardless of the type or the approach direction of the party. At the general rule intersection, both the proportions of car approaches with a TTI_{min} and the mean TTI_{min} values properly reflect the character of the road and whether one has the right of way or not. Similar to the results for free-moving cars, more than 90% of all car

approaches with a TTI_{min} and involved in an encounter, has a TTC_{min} greater than 1.5 s. Again, the moment TTI_{min} occurs, is closely related to the moment of maximum deceleration, but compared with free-moving cars some additional safety margin is gained by decelerating a little longer.

Also in encounters, head movement patterns appear to be typical for the type of intersection. At the yield intersection, neither the presence or the type of party (bicyclist or car), nor the direction the party is coming from, influences the direction of the first head movement. Apparently, when approaching a yield intersection, car drivers unroll a fixed pattern. At the general rule intersection, however, the presence of a party from the right, directs attention and increases the number of first head movements in the direction of the other party (car or bicyclist). Whether the party is a car or bicyclist does not effect the moment the first head movement occurs either. The head movement patterns of road users on the main road (involved in an encounter with a car coming from the right) do differ between car drivers and bicyclists. At the yield intersection, 63% of the car drivers on the main road doesn't display any head movement, and if they look to the right, they look rather late, at only about 1 s away from the intersection. At the general rule intersection, again the presence of the car from the right seems to evoke attention, 83% of the car drivers first looks to the right. Bicyclists, however, display a similar behaviour at both intersections; 63% first looks in the direction of the car at about 3.6 s away from the intersection, 20% looks first to the left, and the remaining 20% doesn't look at all.

Time-To-Collision

Several studies were used to evaluate the TTC measure in normal and more critical interactions between road users. In particular, TTC_{min} indicates how imminent an actual collision has been during the process of approaching each other. In the study on the type of priority regulation, all encounters between a car from the minor road and a car or bicyclist on the main road, as occurring during a given period, were analysed, and therefore, represent for the greater part just normal encounters. The study at the bicycle route intersections, mainly dealt with encounters between bicyclists on the cycle track and intersecting cars. Those interactions were preselected from video on the basis of a collision course expected to be present and an estimated TTC_{min} of less than 2.5 s. These restrictions were applied, on one hand to exclude all encounters that obviously developed without any problem, and on the other hand to include all potentially critical situations. Finally, it was expected that the two calibration studies on Traffic Conflicts Techniques at Malmö and Trautenfels would provide us with both objective and subjective data on critical encounters.

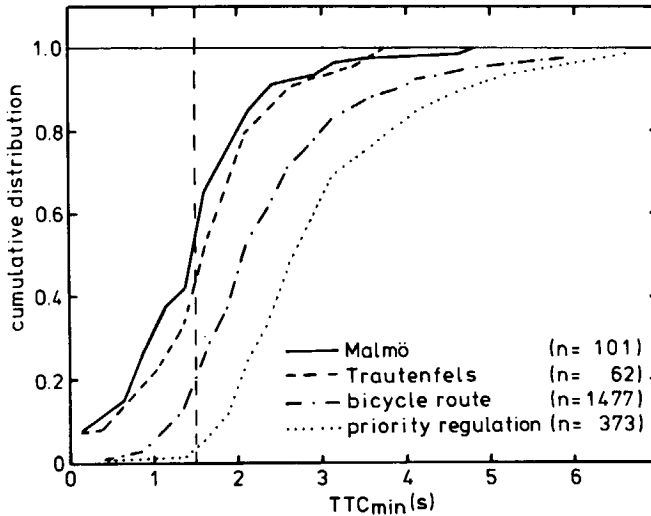


Fig. 5.37 TTC_{min} distributions of conflicts from the Malmö and the Trautenfels calibration studies, and of encounters at bicycle tracks, as well as of all encounters of a given type at a yield and a general rule intersection.

To summarise the results, the cumulative TTC_{min} distributions of all studies are given in Fig. 5.37. Obviously, the interactions scored as conflicts by conflict observer teams in the field, have much lower TTC_{min} values compared with all encounters that occur within a given period at a yield and a general rule intersection. The median TTC_{min} value of conflicts appears to be 1.5 s, whereas encounters, in general, hardly display a TTC_{min} lower than 1.5 s. One half of the encounters displays a TTC_{min} that is greater than 2.6 s. Of course, the data of the conflicts studies represent only a small part of all encounters that occurred at the intersections under study, since the observer teams already made a rigorous selection. The type of intersection doesn't seem to affect this selection process very much.

The car-bicycle encounters that were analysed for the evaluation of bicycle route intersections, have a distribution that lays between the other ones, mainly due to the selection procedure as applied for that study. About 20% of these encounters have a TTC_{min} less than 1.5 s. The encounters at the experimental bicycle route locations with special provisions to emphasise the presence of the cycle track, have significantly higher TTC_{min} values than encounters at control locations without special provisions. At the experimental locations, both the direction the bicyclist is coming from (from the left or from the right) and the direction of crossing by the cars (from or towards

minor road) has an effect on the TTC_{min} distributions, but the proportions of encounters with a TTC_{min} less than 1.5 s are similar. Also the functioning of some specific intersection design elements can be evaluated well by means of the TTC_{min} measure.

Within the group of conflicts as scored by observer teams, the comparison between objective measures and subjective severity scores reveals, on the one hand, that TTC_{min} is a major factor in explaining subjective severity of conflicts, and in this respect, performs better than TTC at the onset of braking. Also the more sophisticated measure $TTCA_{min}$, which assumes a continuation of movement based on a constant acceleration instead of a constant speed for defining a collision course and for calculating the remaining time, doesn't perform as well as TTC_{min} . From the literature evidence is found that the human visual system has difficulty in perceiving a constant acceleration or deceleration as such; subjects tend to extrapolate a constant-acceleration trajectory with a gradually decreasing acceleration [Runeson, 1975] or with a constant acceleration followed by a constant velocity [Jagacinski et al., 1983]. Also the control of catching a ball, for example, is mainly based on an optic variable τ , defined as the time-to-contact if the velocity were to remain constant [Lee et al, 1983]. On the other hand, it also becomes clear that the relation between TTC_{min} and conflict severity scores is not unambiguous; severe conflicts have a low TTC_{min} , but not all conflicts with a low TTC_{min} are regarded as severe. The analysis of encounters with a close proximity between the road users, but not scored by one of the observer teams, suggests that both detection and evaluation of critical encounters may be dependent of the type of road users involved. This is in agreement with the finding that also conflict type relates to conflict severity [Grayson (Ed), 1984]. The large differences among the number of conflicts scored by the various teams, together with the evaluation of conflicts that were scored by only one team, clearly illustrate the detection problems (both 'misses' and 'false alarms') human observers experience in the field on the border line between slight conflicts and encounters. But once a more serious conflict is detected, the evaluation of severity is rather consistently conducted. Based on these results, it can be concluded that, first of all, the TTC_{min} measure is an important variable in discriminating between normal and critical encounters. Furthermore, also with reference to the results of the TTI analysis of how drivers approach an intersection, a minimum value of 1.5 s appears to be of prime importance. No evidence is found that including acceleration explicitly into the definition of TTC would be advantageous; the way the minimum TTC accounts for this, seems to be more appropriate and is in line with empirical findings on visual perception of motion.

Post-Encroachment-Time

The PET measure may be helpful in evaluating a specific type of encounter in which road users just miss each other at relatively high speed and, strictly speaking, no collision course is present. PET describes the final outcome of such events after the encounter has fully developed. In fact, PET is complementary to TTC in situations where no critical collision course is present but where the separation in time between the road users involved is small. In about 25 to 50% of the conflicts as scored by the observer teams in both calibration studies no realistic PET could be calculated, mostly because one of the road users came to a complete stop. Also in rear-end conflicts the PET is not properly defined. The results from the Malmö calibration study reveal that, compared with TTC, typical PET values are rather low with a median PET of 0.8 s and no conflicts with a PET greater than 2 s. Type of intersection doesn't have a systematic effect on PET; conflicts with bicycles involved tend to have relatively low PET values. At the Trautenfels study PET values are higher with a median PET of 1.4 s, but most conflicts with a relatively high PET fall within the lowest severity class and were scored by only one team. However, data of 'normal' PET values in gap-acceptance studies reveal higher values, on an average between 2 and 4 s [i.a. Van der Horst, 1986]. The comparison between objective measures and subjective severity scores doesn't reveal an important contribution of PET when TTC_{min} is included. Only for the PET conflicts from the Trautenfels study, a combination of PET and the speed of the oncoming car resulted in a significant correlation.

Summarising the results, it is concluded that the use of PET as a general measure for evaluating critical encounters is rather limited. For specific situations, however, PET can serve as a complementary measure to TTC. In general, only PET values less than 1 s are experienced as critical, whereas normal PET encounters can be characterized by a PET greater than 2 s.

6 TIME-TO-COLLISION AND DRIVER DECISION-MAKING IN BRAKING

6.1 Introduction

Several observational studies in actual traffic reveal that describing control and driver decision-making strategies of road users in terms of time related measures, such as Time-To-Intersection (TTI) and Time-To-Collision (TTC), give rather consistent results, as was discussed in Chapter 4 and 5. Also in the calibration studies on Traffic Conflicts Techniques, TTC appeared to be one of the major factors in explaining a common severity dimension based on the (subjective) severity scores of human observer teams in the field (Section 5.5). Godthelp [1984] successfully applied the Time-to-Line-Crossing (TLC) concept for analysing driver strategies in lane keeping on both straight and winding roads.

Based on these empirical findings the question arises whether time measures such as TTC are used directly by road users as a cue for decision-making in traffic. From the literature some evidence is found that, in principle, TTC information is directly available to the driver from the optic flow field, and therefore, may serve as an efficient cue in driving [Lee, 1976].

Following a review of the literature on this topic (Section 6.2), Section 6.3 describes a field experiment that was conducted at the University of British Columbia at Vancouver, Canada, to evaluate TTC in relation to drivers' strategy of braking and to investigate the hypothesis that drivers, as moving observers in the environment, use TTC information directly as a cue for decision-making, rather than using information on speed and distance explicitly. The results of this study were reported under contract with the Institute for Road Safety Research SWOV [Van der Horst and Brown, 1989].

6.2 Review of the literature

The research on traffic conflicts indicates individual observers seem to be able to make use of a time related measure such as TTC when evaluating interactions between road users. Hayward [1972] suggested that this ability was based on skills developed as a moving observer during every day driving.

Lee [1976] suggested that drivers are able to control braking based on visual information from the optic flow field. For example, in a car-following situation TTC information from the optic flow field (i.e. the visual angle by which the lead vehicle is seen, divided by the visual angular velocity) would enable the driver:

- a) to determine if he is on a collision course,
- b) to judge when to start braking, and
- c) to control the braking process itself.

Lee states that information from the optic flow field is likely to be used directly rather than information on distance and speed explicitly. In the latter approach TTC is obtained by dividing the distance to the lead vehicle by the approach speed in a cognitive process. In the literature several empirical findings on people's ability to estimate TTC are reported in order both to support and to reject Lee's theory. Following a brief description of human sensitivity in detecting an impending collision (Section 6.2.1), Section 6.2.2 reviews the literature on estimates of TTC, and in Section 6.2.3 the reason why the present study has been conducted is discussed.

6.2.1 Detection of impending collision

Janssen et al. [1976] have shown that people appear to be sensitive in detecting a receding or approaching movement relative to a lead vehicle. They presented threshold values for a car-following situation with only the tail-lights visible. A stimulus presented at threshold value allows the subject to detect a receding or approaching movement 75% of the time. In Fig. 6.1 their data are converted to threshold values of TTC as a function of approach speed for different viewing times and object widths. Above a viewing time of 2 s no improvement in detection of movement is present. With a viewing time of only 0.5 s the TTC threshold value in a car-following situation (with two tail-lights at a separation of 1.4 m) enables ample time to react up to a speed of about 25 m/s. The hatched area in Fig. 6.1 indicates when it becomes critical given a reaction time t_r of 1.5 s and an average required acceleration rate ACC_{req} of -3 m/s^2 , according to Eq. (4):

$$TTC = t_r - \frac{V}{2 \cdot ACC_{req}} \quad (4)$$

Eq. (4) gives the TTC value at the moment of detection that is needed to prevent a collision when braking with a deceleration rate of $-ACC_{req} \text{ m/s}^2$ is started after a reaction time of t_r s. Janssen et al. [1976] also found that the presence of a context background had no influence on the results.

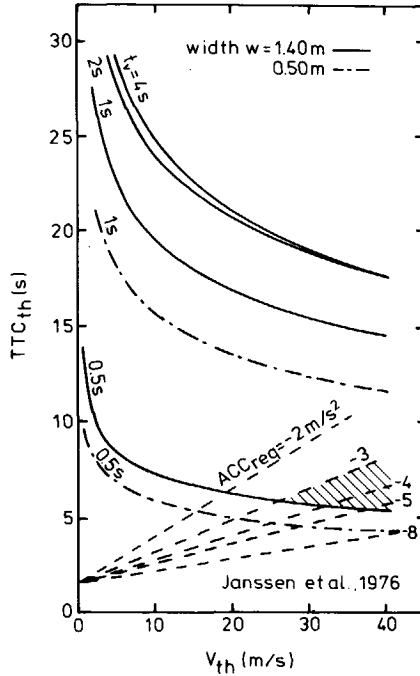


Fig. 6.1 Threshold values of Time-To-Collision (TTC_{th}) (s) for detection of impending collision as a function of approach speed V_{th} (m/s), viewing time t_v (s), and separation between tail-lights w (m) of lead vehicle in darkness. The fan of straight lines gives the moments braking with a given acceleration ACC_{req} (m/s^2) has to start after a reaction time of 1.5 s to prevent a collision.

6.2.2 Estimates of Time-To-Collision

In the literature estimates of Time-To-Collision for both laboratory and field experiments are reported. The basic premise of these studies is that, if TTC information from the optic flow field is directly to be used, people must be able to estimate TTC accurately. Schiff and Detwiler [1979] presented short movie clips of objects approaching the film camera. At a given TTC before the object reached the camera (ranging from 2 to 10 seconds) the clip ended and the subject was asked to press a button at the moment he thought the collision would have occurred. Judgments of TTC appeared to be best predicted by two-dimensional rate of angular-size-change in the optic flow field, invariant over object size, distance, and approach velocity. No improvement was found for adding distance information by a background grid or by presenting an approaching car in a real-life environment. However, the TTC was

consistently underestimated and substantial individual differences were found. McLeod and Ross [1983] included some aspects of a moving observer by using film clips taken in a moving car approaching a stationary target car. Viewing times varied between 2 and 6 seconds with the hypothesis that an increase in accuracy of TTC estimates with an increasing viewing time would occur when observers include distance and speed information explicitly in their judgments (referred to as the "cognitive method"). Alternatively, if the "optic flow method" predominated, performance should not improve with increased viewing time. Subjects had to respond verbally. TTC values ranged from 3.6 to 9 seconds. No effect of viewing time on TTC estimates was found, accuracy was deteriorating rapidly for $TTC > 8$ s, and males appeared to give higher and more accurate estimates than females. However, their conclusion that viewing time has no effect and, therefore, supports the optic flow method, is at the least premature given the threshold values found by Janssen et al. [1976], see Section 6.2.1. It is unlikely, even if information on distance and speed is used separately, that larger viewing times will considerably improve visual perception.

Cavallo et al. [1986] argued that the findings of these studies might be influenced by the poor possibilities in evaluating speed and distance from the two-dimensional film clips. Therefore, they conducted a field experiment where both experienced and inexperienced drivers, approaching a stationary mockup of the rear of a car, had to indicate the moment they thought the cars would collide by pressing a button. The viewing time was 3 seconds, after which the view was occluded and the object removed. TTC values were 3 and 6 seconds. The experienced drivers produced much better estimates (although still underestimated) than the inexperienced ones. A restriction of the visual field from normal to 10 degrees of visual angle deteriorated the estimates of the inexperienced drivers only. So, experienced drivers seem to be able to gather the necessary information from the expansion rate of the object (TTC information) while inexperienced drivers lack speed information from the peripheral visual field.

In spite of the different stimuli and procedures used, all three studies indicate TTC values are consistently underestimated. In Fig. 6.2 the average estimated TTC values are plotted against the actual TTC values.

The relation between TTC_{est} and TTC can be described well by a power function according to the psychophysical law of Stevens [1957], which states that, in general, a human response value is related to the stimulus value by:

$$\text{Response} = b * (\text{Stimulus})^n \quad (5)$$

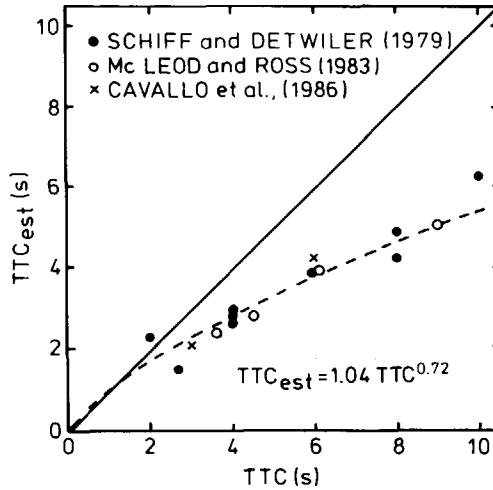


Fig. 6.2 Relation between estimated (TTC_{est}) and actual (TTC) Time-To-Collision based on a Stevens' function (data from Schiff and Detwiler [1979], McLeod and Ross [1983], and Cavallo et al. [1986]).

The parameters b and n can be derived by a linear regression fit through a log transformation on the data, resulting in:

$$TTC_{est} = 1.04 * TTC^{0.72} \quad (6)$$

The fit of Fig. 6.2 suggests that for $TTC < 2$ s one can produce rather accurate estimates. For higher values underestimates increase with TTC . Both Schiff and Detwiler [1979] and McLeod and Ross [1983] indicate that subjects use a time memory span of about 8 s, implying that estimates of high TTC values become very inaccurate.

Groeger and Brown [1988] used video tape to examine the approach to and passing of a stationary vehicle instead of actual collision courses. For a 40° field of view with for the greater part small TTC values (0.33, 0.99, 1.32 and 3.96 s at the end of the viewing time) they reported no systematic underestimation of time. For a 10° field of view (with TTC values of 1.37, 4.12, 5.49 and 16.46 s) they found, as did the other authors, an underestimation for 96% of the trials. However, the different TTC values at the end of viewing time between conditions do not permit a proper interpretation of their results. Besides, the absence of a real collision course in their stimuli (detected either from the optic flow field or from the lateral distance to the centre

line present) does not require any action in actual driving conditions. Therefore, estimates of approach variables seem less relevant.

In actual driving it is clear that an accurate timing of the moment an evasive action has to be initiated is more relevant than a good estimate of the moment one would actually collide. Therefore, an explanation for the systematic underestimation of TTC might be that drivers rather tend to estimate the moment of action, rather than the moment of coincidence. In a field experiment Malaterre et al. [1987] instructed subjects to indicate the latest instant they thought they would be able to conduct a stop successfully while approaching a stationary line marked by cones. The approach speed varied between 40 and 120 km/h (11.11 - 33.33 m/s). No real braking manoeuvres were conducted. For each speed class Fig. 6.3 gives the mean values for the required TTC. The data points can be described well by a linear regression fit (dotted line) ($r=0.955$):

$$TTC_{br} = 1.7 + 0.05 * V \quad (7)$$

With a mechanical response time for the braking system of 0.4 s [Malaterre et al., 1987] and a given acceleration rate ACC_{req} the latest instant such a brake action has to start is given by:

$$TTC_{br} = 0.4 - V / (2 * ACC_{req}) \quad (8)$$

For different deceleration rates these lines are given in Fig. 6.3 as well. Malaterre et al. computed for each individual trial the required deceleration rate following a mechanical response delay for the braking system of 0.4 s. The mean required deceleration rate increases with speed, as shown in Fig. 6.3. In research on drivers' decision-making at signalised intersections the same result occurred: viz., at higher approach speeds higher mean deceleration rates are needed [Van der Horst and Wilmlink, 1986]. Assuming a linear relationship between required acceleration and speed the data of Malaterre et al. result in ($r=0.88$, $p<0.01$):

$$ACC_{req} = - 2.574 - 0.187 * V \quad (9)$$

By combining Eqs. (8) and (9) the TTC_{br} can be formulated as a function of speed, according to:

$$TTC_{br} = 0.4 + \frac{V}{5.15 + 0.37 * V} \quad (10)$$

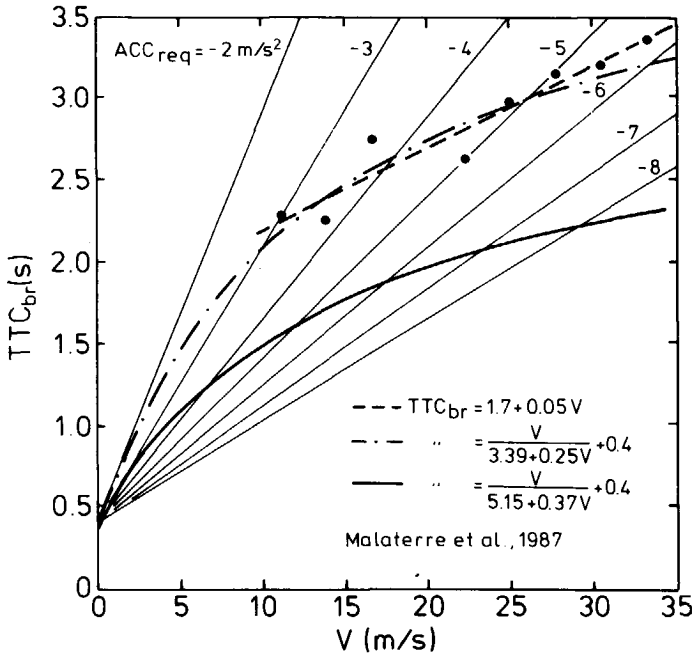


Fig. 6.3 Time-To-Collision (TTC_{br}) values (s) at the latest moment the onset of braking is thought to be successful as a function of speed V (m/s). The fan of lines gives the moments braking with a given acceleration ACC_{req} (m/s^2) has to start. The data points present average TTC_{br} values, the solid curved line indicates the resulting TTC_{br} given a linear fit between averaged required deceleration and speed; the dotted curve is a best fit of average TTC_{br} assuming a general linear relationship between ACC_{req} and V .

In Fig. 6.3 this relation is presented by a solid curve. This approach results in much lower TTC values than the average TTC values for each speed indicated. Although the average TTC_{br} is fitted well by a straight line according to Eq. (7), the characteristics of the relationship between TTC_{br} and V at low speeds may be rather different from a linear one. A possible approach may be to assume a linear increase of the required deceleration with speed and to use the general form of Eq. (10) to fit the data. This results in the broken curve in Fig. 6.3, according to:

$$TTC_{br} = 0.4 + \frac{V}{3.39 + 0.25 \cdot V} \quad (11)$$

Malaterre et al. did not include the average TTC values in their report, because individual subjects appeared to use different strategies. Some of them have a strategy where the minimally required TTC increases with speed. Some others estimate the required TTC more independently on speed and use one constant TTC value. The latter strategy results in the highest number of impossible manoeuvres. A limited additional experiment where subjects were asked to indicate the instant they would start normal braking resulted in the same strategy for the individual subjects [Malaterre et al., 1987].

6.2.3 Conclusions

As Groeger and Brown [1987] state, the studies on the estimates of Time-To-Collision [Schiff and Detwiler, 1979; McLeod and Ross, 1983; Cavallo et al., 1986] are far from conclusive regarding which of the competing theories (optic flow or cognitive method) best accounts for the data reported. But their study on estimates of TTC [Groeger and Brown, 1988] also does not permit a proper interpretation since their field of view conditions were confounded with the size of actual TTC at the end of the viewing period.

In the research on TTC estimates, the experimental procedure puts a rather large demand on the level of cognitive information processing while it may be expected that the process we are looking for takes place on a more automatic level of control. One should not ask subjects to indicate the hypothetical moment they would collide, or the moment an evasive action has to start. Let them perform as if in actual traffic and record when they make their decisions and how they react. The present study starts from this viewpoint and aims to evaluate TTC in relation to driver's strategy of braking and to investigate what information is more likely to be used.

6.3 The Vancouver experiment

6.3.1 Introduction

As discussed in the previous section no experimental data on TTC are available in situations where the subjects actually have to take evasive action to avoid a collision. The simple traffic situation of approaching a stationary object seems to be advantageous to start with because it implies a well-defined collision course with a corresponding TTC curve over time. In Section 3.3.1, Fig. 3.3 shows what happens in this simple situation, and illustrates the parameters TTC_{br} and TTC_{min} , being the TTC at the onset of braking and the minimum TTC that is reached during the approach,

respectively. The decision to start braking may be linked to the perception of TTC_{br} . TTC_{min} describes how imminent a collision has been during the braking process itself.

Fig. 6.4 illustrates three hypothetical strategies drivers might use for determining the moment to start braking dependent on their approach speed (V), viz.:

- The use of a constant distance at the onset of braking ($DIST_{br}$) independent on V , resulting in a quadratic increase of the required deceleration to stop successfully, and a linearly decreasing TTC_{br} ,
- The use of a constant TTC_{br} over V , resulting in a linear increase of the required deceleration and a linearly increasing $DIST_{br}$, and
- The use of a constant level of required deceleration over V , resulting in a quadratic relation between $DIST_{br}$ and V , and a TTC_{br} linear with V .

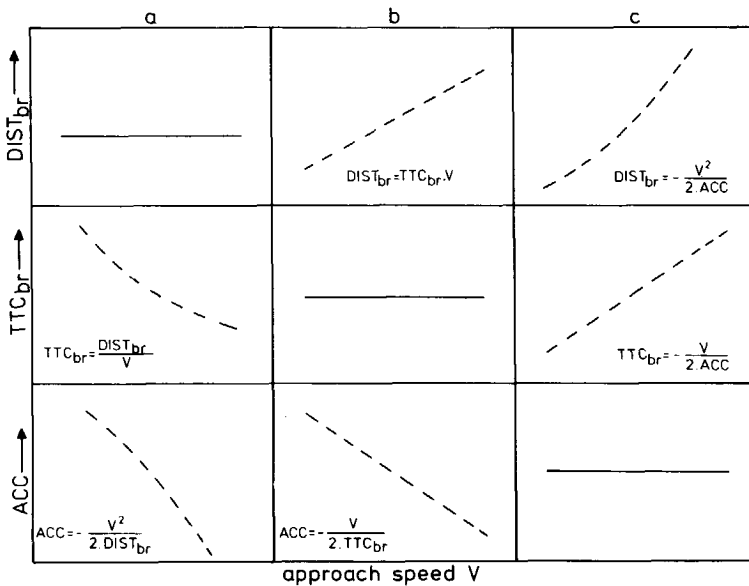


Fig. 6.4 Schematic representation of different strategies drivers might use to determine when to start braking in approaching a stationary object with a given approach speed V ; Fig. 6.4a is based on a constant distance at the onset of braking ($DIST_{br}$), Fig. 6.4b on a constant Time-To-Collision at the onset of braking (TTC_{br}), and Fig. 6.4c on a constant level of required deceleration (negative acceleration ACC).

A possible solution for the problem of how to investigate what information is more likely to be used, may be to exclude one element in the visual input to the driver,

and to see whether his performance deteriorates. Riemersma [1987] suppressed lateral velocity information during driving by applying a stroboscopic occlusion technique. During his experiments subjects wore electronically driven liquid crystal glasses, which could be made transparent (open) or light scattering (closed) [Milgram, 1987]. A 10 ms open period at a frequency of five times per second adequately suppressed velocity information. The short viewing time of 10 ms was chosen to prevent any processing of velocity information in a single presentation. This technique of stroboscopic occlusion may also be adequate to suppress TTC information that is directly available from the optic flow field. In an earlier experiment Riemersma [1984] had shown by using a cross-modality matching procedure that subjects even under this 5 Hz occlusion condition are able to adjust their physical speed in a consistent manner. So, if TTC information is used directly by drivers as a cue to their decision-making, it is to be expected that a 5 Hz stroboscopic occlusion would considerably deteriorate drivers' performance. A 25 Hz occlusion would still enable a cognitive evaluation of speed based on successive displacement and, therefore, would not deteriorate drivers' performance if the distance and speed information is explicitly used in their judgment.

6.3.2 Method

To investigate driver's strategy of braking a field experiment was conducted at a road section closed for other traffic. Subjects were instructed to drive an instrumented car at a given constant speed while approaching a stationary object (simulated rear end of a passenger car) and to start braking according to either a normal or a hard braking instruction (see details later).

Subjects

Some studies indicate drivers tend to the greater use of time related information with increasing driving experience. Therefore, a distinction between experienced and inexperienced drivers was made.

Twelve male subjects, all students at the University of British Columbia and ranging in age from 18 to 30 years participated in this study. Two groups (six subjects each) were selected according to the level of driving experience:

- Inexperienced drivers with a driving licence but with a driving experience of less than 10,000 km, and
- experienced drivers with a driving licence for at least three years and a driving experience of over 100,000 km.

The subjects were paid for their participation. Their final earning depended partly on their success in performing the task well.

Road section

The road section consists of a part of a former runway at the Boundary Bay Airport, Vancouver, B.C. with a length of about 540 m and a width of 60 m without road markings. The lay-out of the test track is given in Fig. 6.5.

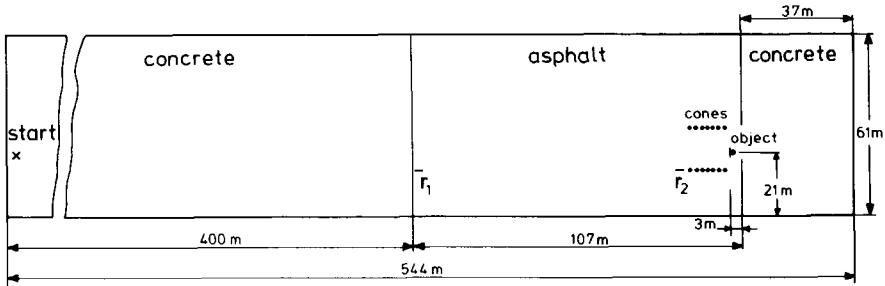


Fig. 6.5 Lay-out of the test track at Boundary Bay Airport.

Stationary object

The object was made of a styrofoam plate characterising the shape of the rear end of a small compact car, see Fig. 6.6. The main features implemented were the taillights (red colour) imbedded in a light blue body, the bumper in black, and a silver painted rear window. The object was mounted on a plastic barrel.

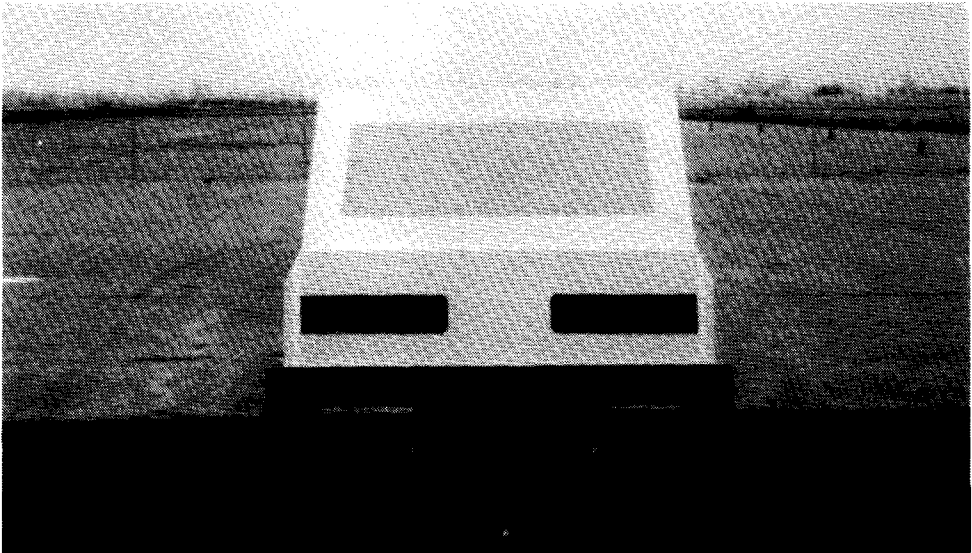


Fig. 6.6 Stationary object simulating the rear end of a small passenger car.

Instrumented Car

The instrumented car used in this experiment is a Dodge Mini Ram Van equipped with front wheel drive, power steering, power brakes, and a five speed manual gear. An on-board Silent-Witness vehicle monitoring computer SW 100 registers vehicle speed and distance travelled by counting impulses from a Hall transducer mounted on the drive shaft together with the status of ten binary input lines at a sample rate of 10 Hz. A Toshiba T1100plus lap top computer was used for on-line downloading of the data. One binary input line was connected with a switch on the brake pedal and another with a pulsed beam infrared detector that fired at the moment a reflector pole (r_1 or r_2 in Fig. 6.5) was passed. These registrations enabled the following measurements:

- distance travelled with time,
- longitudinal speed with time,
- moment of initiating braking action, and
- moment of passing reflector pole r_1 , r_2 , respectively.

Instruction

Before driving, subjects had to read a written instruction. They were instructed to drive at a given constant speed while approaching the stationary object. One of the following braking instructions was given:

- 1) start hard braking (but without locking the wheels) at the latest moment you think you are able to stop in front of the object, or,
- 2) start normal braking at the latest moment you think you can stop safely in front of the object.

Subjects had to avoid both hitting the object and stopping much too early. Their final earnings partly depended on their success in performing this task well.

Occlusion

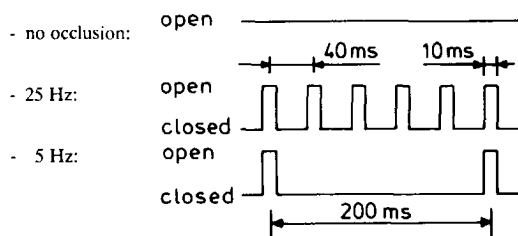


Fig. 6.7 Three conditions of visual occlusion by applying electronically driven liquid crystal glasses.

According to the procedure of Riemersma [1987], two conditions of stroboscopic visual occlusion were applied (25 Hz and 5 Hz), together with one control condition of continuous view while wearing the spectacles. The three conditions of visual occlusion are visualised in Fig. 6.7.

Procedure

Three levels of approach speeds were used, namely:

30, 50 and 70 km/h

with three replications of each.

In this way each subject had to conduct 2 (instruction) * 3 (occlusion) * 3 (speed) * 3 (replications) = 54 trials in all. These trials were divided into two blocks of 27 trials each for each instruction. Half of the subjects started with the normal braking and the other half with the hard braking instruction. Within each block the trials were presented in random order.

Before the actual experiment started several test trials were conducted to get the subject used to driving the instrumented car and to the experimental procedure. Also a calibration run was made. Each trial started at a distance of about 500 m from the object. The subject was told which speed he had to drive and which occlusion condition he would experience. He had to accelerate as quickly as possible and maintain the desired speed according to instructions of the experimenter seated at the passenger front seat. At a distance of about 200 m from the object the spectacles were switched from continuous view to the desired occlusion mode. To have a check on the absolute position measurement an observer outside the car estimated the distance to the object with the help of two rows of cones after the car had stopped. If braking was conducted with locking wheels the skid marks were measured with a measuring tape. If the object was hit the displacement was measured too with a measuring tape and, if necessary, the object replaced.

Data analysis

Based on the moment of passing reflector r_2 the absolute position of the instrumented car was derived from the distance travelled for each sample. With that the distance to the object (DIST) during the approach, the distance to the object at the onset of braking (DIST_{br}) and the final stop distance (DIST_{stp}) were calculated. The longitudinal speed (V) was filtered twice by a second order polynom filter with length 11 before the acceleration (ACC) was calculated by differentiating the speed. The minimum acceleration (maximum deceleration) as reached during the braking is

referred to as ACC_{min} , and the average acceleration required at the onset of braking to come to a successful stop as ACC_{req} .

In defining TTC one has to make assumptions about the extrapolation of the vehicle movement from the current observation. Mostly, the extrapolation of movement is inferred from a constancy of speed, resulting in:

$$TTC = \frac{DIST}{V} \quad (12)$$

TTC at the onset of braking is referred to as TTC_{br} and the minimum TTC as reached during each approach as TTC_{min} .

Differences between conditions were tested by analysis of variance (ANOVA) for the variables $DIST_{br}$, $DIST_{stp}$, ACC_{req} , ACC_{min} , TTC_{br} , and TTC_{min} . Because a first ANOVA revealed that each first trial of a condition differed from the second and third trial for most of the variables, while the second and third trial did not, the first trial of each condition was excluded from further analysis and the second and third trial were taken as replica in the ANOVAs.

6.3.3 Results

Table XXVI summarises the significant results of the ANOVAs for all variables. Given are the estimated percentages of explained variance accounted for by main and interaction effects.

6.3.3.1 The onset of braking

Three dependent variables are related to the onset of braking, as defined by the moment the switch on the brake pedal was activated, viz. $DIST_{br}$, TTC_{br} , and ACC_{req} .

Driving experience does not reveal any systematic effects on each of these variables. Braking instruction, speed, and occlusion, however, all show significant main effects on $DIST_{br}$, TTC_{br} , and ACC_{req} . Fig. 6.8 gives the effects of braking instruction, speed, and occlusion. The largest main effect on $DIST_{br}$ is due to speed, $F(2,20) = 658.$, $p < 0.001$, followed by braking instruction, $F(1,10) = 92.8$, $p < 0.001$. Instruction and speed also show an interaction effect, $F(2,20) = 17.2$, $p < 0.001$, indicating that at higher speeds the difference due to instruction increases. Occlusion has only a small effect on $DIST_{br}$, $F(2,20) = 11.0$, $p < 0.001$. Instruction has a large main effect on TTC_{br} , $F(1,10) = 101.0$, $p < 0.001$. Also TTC_{br} increases with speed, $F(2,20) = 51.2$, $p < 0.001$, but to a less extent than $DIST_{br}$. With occlusion subjects take an extra safety time margin, $F(2,20) = 24.8$, $p < 0.001$. The effect of the 5 Hz occlusion is the largest, but also the 25 Hz occlusion increases TTC_{br} .

Table XXVI Estimated percentages of explained variance for each of the dependent variables. The independent variables are: E experience, I instruction, S speed, O occlusion, Ss subjects (within experience).

	df	DIST _{br}	DIST _{stp}	TTC _{br}	TTC _{min}	ACC _{req}	ACC _{min}
E	1	-	4.1*	-	-	-	-
I	1	17.1**	-	39.6**	5.8*	28.3**	53.8**
S	2	57.1**	-	6.6**	2.4+	30.8**	8.7**
O	2	1.2**	20.2**	5.5**	18.8**	4.0**	1.6*
E x O	2	-	4.2*	-	2.2*	-	-
I x S	2	2.0**	-	-	-	0.8*	-
I x O	2	-	-	-	1.2+	-	-

Ss(E)	10	9.2**	3.1**	21.6**	7.0**	13.0**	15.6**
Ss x I	10	2.0**	5.6**	4.3**	2.8**	2.5**	3.9**
Ss x S	20	0.6*	3.4*	0.7+	4.3**	0.7+	-
Ss x O	20	1.0**	4.2**	1.9**	1.9+	1.5**	1.7**
Ss x I x O	20	0.5*	2.2*	1.1*	2.6*	0.9*	-
Ss x S x O	40	1.4**	5.6**	3.9**	6.0**	1.9**	1.8**
error variance	216	8.0	43.5	15.1	39.8	15.9	13.4

+ $p < 0.05$, * $p < 0.01$, ** $p < 0.001$

There are considerable differences among subjects, $F(10,216) = 52.3$, $p < 0.001$, that are also dependent on instruction ($F(10,216) = 11.3$, $p < 0.001$), speed ($F(20,216) = 1.88$, $p < 0.05$), and occlusion ($F(20,216) = 3.03$, $p < 0.001$). With occlusion subjects' decisions to start braking change differently with speed (subject x speed x occlusion, $F(40, 216) = 3.34$, $p < 0.001$). Without occlusion all subjects display a TTC_{br} that increases with speed (mean slope = 0.018, standard deviation (s.d.) = 0.0067). With the 25 Hz occlusion also all slopes are positive (mean slope = 0.014, s.d. = 0.009). With the 5 Hz occlusion (mean slope = 0.008, s.d. = 0.0188) however, the variability among subjects is much greater ($F(11,11) = 7.87$, $p < 0.01$) with four of them (25%) having a TTC_{br} that decreases with speed.

At higher speeds higher minimally required deceleration rates at the onset of braking (negative ACC_{req}) are needed to come to a successful stop ($F(2,20) = 231.$, $p < 0.001$). The main effect of instruction ($F(1,10) = 116.$, $p < 0.001$) indicates that, in general, subjects are able to implement the normal or hard braking instruction well.

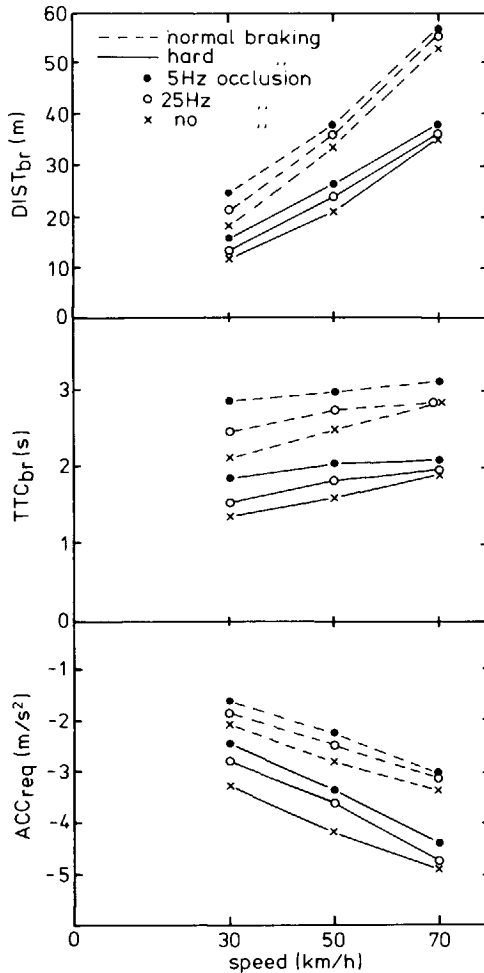


Fig. 6.8 Effects of braking instruction, speed, and occlusion on the dependent variables at the onset of braking.

A small interaction effect between instruction and speed occurs ($F(2,20) = 7.14, p < 0.01$); with the hard braking instruction the increase in required deceleration with speed is higher than with the normal braking instruction. Because of the extra safety margin subjects take, occlusion results in relatively smaller required deceleration levels ($F(2,20) = 21.4, p < 0.001$). Again, considerable differences among subjects exist ($F(10,216) = 30.5, p < 0.001$), also dependent on instruction, speed and occlusion. ACC_{req} at the onset of braking represents only a hypothetical value since

in actual braking it takes some small amount of time before a given deceleration level is reached. Malaterre et al. [1987] give an average response time of the braking system of about 0.4 s. This will result in higher required deceleration rates. As an example, Fig. 6.9 gives TTC_{br} as a function of speed for the no occlusion condition together with a fan of lines that represents a constant required deceleration model with the 0.4 s delay time included. With hard braking ACC_{req} ranges from about -4 m/s^2 at a speed of 30 km/h to -6 m/s^2 at 70 km/h.

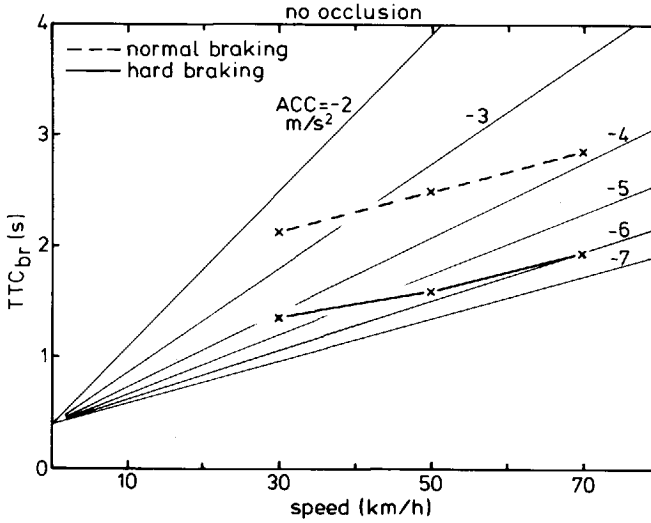


Fig. 6.9 TTC_{br} as a function of approach speed for both the normal and hard braking instruction without occlusion. The fan of lines represents the moments braking has to start with a given negative acceleration ACC after a response time of the braking system of 0.4 s.

6.3.3.2 The control of braking

The onset of braking is followed by the control of the braking process itself. In actual braking no uniform deceleration rate will occur right from the beginning, it takes some time to reach a given level, and almost always a distinct maximum deceleration (minimum negative acceleration) (ACC_{min}) can be observed. The minimum TTC value that is reached during the braking (TTC_{min}) indicates how imminent a collision has been. A third parameter that describes the final result of the braking process is the stopping distance to the object ($DIST_{stp}$).

As could be expected, the largest effect on ACC_{min} is due to the braking instruction, $F(1,10) = 153.$, $p < 0.001$, see Fig. 6.10. But also speed ($F(2,20) = 135.$, $p < 0.001$) and to a less extent occlusion ($F(2,20) = 8.66$, $p < 0.01$) affects the maximum deceleration level that is reached during braking. Without occlusion the highest maximum deceleration levels occur.

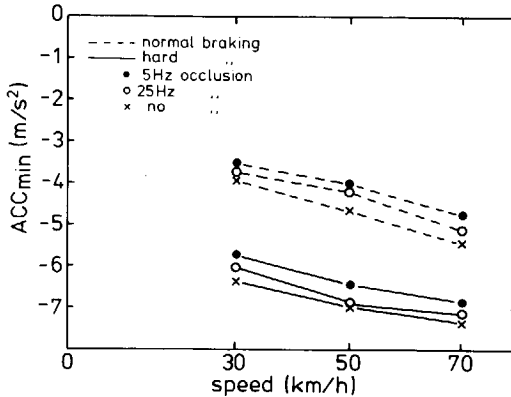


Fig. 6.10 Effects of braking instruction, speed, and occlusion on the mean minimum acceleration ACC_{min} (maximum deceleration) as reached during the control of braking.

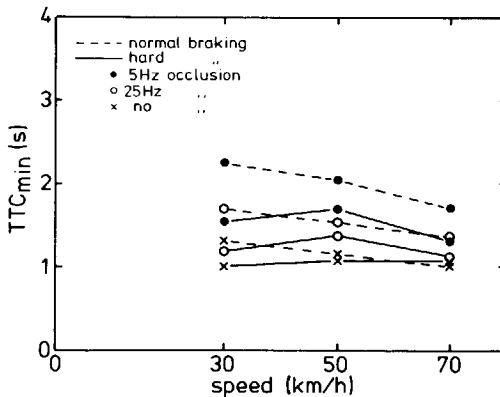


Fig. 6.11 Effects of braking instruction, speed, and occlusion on the minimum TTC (TTC_{min}) as reached during the control of braking.

The largest effect on TTC_{min} is due to occlusion ($F(2,20) = 55.2$, $p < 0.001$), see Fig. 6.11. Without occlusion TTC_{min} is rather independent of speed, instruction, or driving experience, and reaches a value of about 1.1 s, on an average. With occlusion TTC_{min}

is much larger and dependent on instruction (main effect of instruction $F(1,10) = 19.1$, $p < 0.001$; instruction \times occlusion: $F(2,20) = 3.9$, $p < 0.05$).

Also the differences between subjects are substantial, $F(10,216) = 7.33$, $p < 0.001$, and dependent on speed ($F(20,216) = 2.93$, $p < 0.001$), instruction ($F(10,216) = 3.51$, $p < 0.001$), and occlusion ($F(20,216) = 1.88$, $p < 0.05$). Again, the second order interaction subject \times speed \times occlusion ($F(40,216) = 2.37$, $p < 0.001$) shows up, revealing that by occlusion the control of braking by individual subjects changes differently with speed. Driving experience shows an interaction effect with occlusion ($F(2,20) = 8.58$, $p < 0.01$) in that the increase in TTC_{min} by occlusion is stronger for the inexperienced drivers than for the experienced ones. In total 12 approaches (1.9% of all approaches) finally resulted in an actual collision with the object, six of which occurred with the 5 Hz occlusion.

The moment TTC_{min} occurs, is closely related to the moment of maximum deceleration; on an average, the difference between both moments, t_{dif} being $t_{ACCmin} - t_{TTCmin}$, is rather small without occlusion, viz. -0.18 s for the normal braking instruction and 0.21 s for the hard braking instruction. However, t_{dif} appears to be dependent of speed and braking instruction, see Fig. 6.12 (ANOVA, effect of speed, $F(2,20) = 25.6$, $p < 0.0001$, 12.6% of explained variance; effect of instruction, $F(1,10) = 10.6$, $p < 0.01$, 4.3% of explained variance; speed \times instruction, $F(2,20) = 3.53$, $p < 0.05$, 1.2% explained variance).

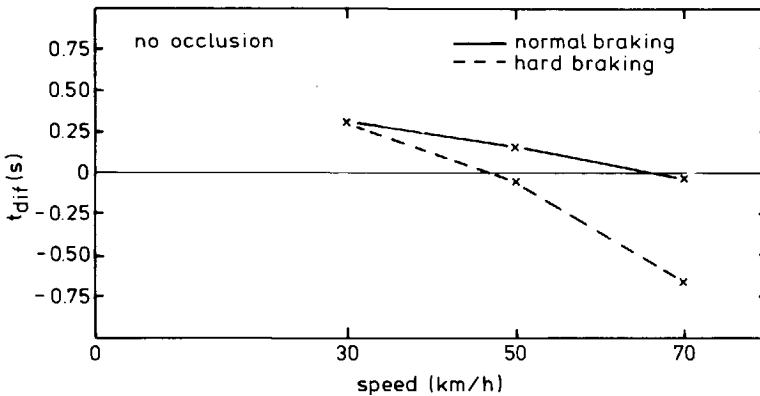


Fig. 6.12 Effects of braking instruction and speed on mean t_{dif} without occlusion.

From ANOVA no systematic effects of occlusion are found. But a comparison between cumulative t_{dif} distributions of the conditions without and with 5 Hz

occlusion per braking instruction reveals that with 5 Hz occlusion relatively more positive values occur (Kolmogorov-Smirnov test, normal braking, $D_{\max} = 0.222$, $p < 0.01$; hard braking, $D_{\max} = 0.297$, $p < 0.001$), see Fig. 6.13. With the 5 Hz occlusion, also the variability among trials is greater; for both the normal and hard braking instruction the variance of the 5 Hz occlusion condition is significantly greater than without occlusion, viz. 1.36 vs. 0.80 ($F(107,107) = 2.89$, $p < 0.01$), and 0.60 vs. 0.44 s ($F(107,107) = 1.86$, $p < 0.001$), respectively.

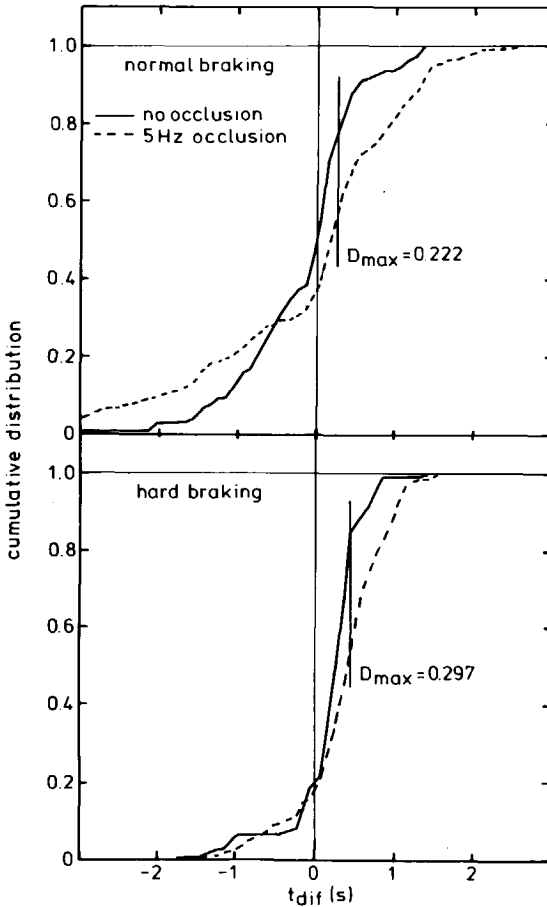


Fig. 6.13 Effects of occlusion on the cumulative t_{dif} distributions of both braking instructions.

Neither braking instruction nor speed displays any systematic effects on the stopping distance $DIST_{stp}$. Only occlusion has a large main effect on $DIST_{stp}$ ($F(2,20) = 37.6$, $p < 0.001$), Fig. 6.14. Driving experience only has a main effect on $DIST_{stp}$ ($F(1,10) = 12.6$, $p < 0.01$); on an average, experienced drivers appear to be able to come to a stop about 1.2 m closer to the object than do the inexperienced drivers, and the interaction experience \times occlusion ($F(2,20) = 8.58$, $p < 0.01$) indicates that they are less sensitive to occlusion.

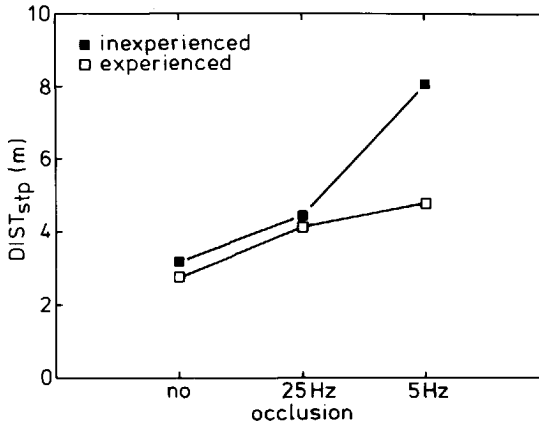


Fig. 6.14 Effects of driving experience and occlusion on the stopping distance $DIST_{stp}$.

6.4 Discussion and conclusions

The aims of this study were to explore drivers' strategies of braking in approaching a stationary object in relationship to the TTC measure and to investigate if TTC information from the optic flow field is more likely to be used than information on speed and distance explicitly.

Drivers' strategy of braking

Without occlusion a rather consistent braking behaviour is displayed with respect to both the onset of braking and the control of the braking process itself.

All subjects have a strategy where 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 in Fig. 6.9 (given a brake response time of 0.4 s). At higher speeds higher mean deceleration levels are needed to come to a successful stop. This is in line with the findings of Malaterre et al. [1987], and also at signalised intersections higher approach speeds lead to higher mean required deceleration levels [Van der Horst and

Wilmink, 1986]. But contrary to the results of Malaterre et al. [1987], we did not find large differences in the increase of TTC_{br} over speed among subjects. Mainly the absolute level differed, indicating that each subject has his own criterion level. Malaterre et al. reported that some subjects had a strategy by using a rather constant TTC_{br} value over speed resulting in the highest number of impossible manoeuvres. A major difference between their approach and ours was that their subjects did not get feedback since no actual braking was involved. Within the range of speeds used in our experiment (30 - 70 km/h) the data suggest a linear relationship between TTC_{br} and speed, but it may be well be that at higher speeds the curve levels off as is the case for the results of Malaterre et al. who included speeds up to 120 km/h (Fig. 6.3). Our results are the closest to the solid curve in Fig. 6.3 based on a linear relationship between speed and required deceleration levels averaged for each class of speed.

The control of the braking process is conducted in such a way that TTC reaches a minimum of about 1.1 s and this is independent on speed or braking instruction. This constancy of TTC_{min} over both braking instruction and speed suggests that drivers make use of a kind of a safety margin one don't like to exceed. In general, the moment the deceleration reaches its maximum, gives an indication of the moment the driver knows a collision will be successfully avoided. The close relationship between the moment of maximum deceleration and of minimum TTC suggests, that TTC_{min} is an important variable in controlling the braking process.

TTC information from the optic flow field

The consistent underestimation of TTC as found in the studies discussed in Section 6.2.2, are in line with results from psycho-physical experiments where time is the only perceptual cue available [i.a. Stevens, 1957; Fraisse, 1964; Michon, 1967]. So, for that reason none of the studies on estimating TTC would reject the hypothesis of direct use of TTC information from the optic flow field. In our experiment the technique of stroboscopic occlusion was applied to suppress the TTC information directly available from the optic flow field. Stroboscopic occlusion substantially deteriorates the braking performance of both the experienced and inexperienced drivers. The 5 Hz occlusion, when presumably only position information is available in the optic flow field [Riemersma, 1987], was experienced by all subjects as most difficult. Most subjects had difficulty in heading to the object in a straight line, and reported that they were quite uncertain when to start braking. This resulted in a wide range of TTC_{br} values and a great variability between and within subjects. Frequently, braking started much too early resulting in a stopping distance of over 15 meters from the object. On the other hand 50% of the collisions occurred in the 5 Hz condition. Driving experience does not have much influence on the decision when to start braking. Effects of

driving experience only show up for the control of braking and the final result of the stopping distance, mainly because inexperienced drivers under the most difficult condition of occlusion (5 Hz) maintain a much greater margin. With 5 Hz occlusion experienced drivers seem to be able to compensate for their early decision to start braking in a later stage of the approach when they are close to the object. The results of Cavallo et al. [1986] suggest that experienced drivers have developed the skill to make use of TTC information from the optic flow field. If so, it is to be expected that experienced drivers are relatively more affected by excluding this information than are inexperienced drivers. That the interaction effect of driving experience and occlusion does not show up for the onset of braking is probably due to the fact that the 5 Hz occlusion condition deteriorates the visual input too drastically for both groups of drivers. Another explanation may be that the skill of using optic flow information is developed in a very early stage of learning, and for that reason our inexperienced group is already "too experienced". Unfortunately, Cavaillo et al. did not specify the criteria they used to define driving experience.

Of course, the 5 Hz stroboscopic occlusion also deteriorates the visual perception of the longitudinal velocity itself. But Riemersma [1984] showed that also with the 5 Hz occlusion drivers are still able to adjust their speed well in a cross-modality matching procedure, probably based on other cues that are available to the driver in actual driving. Also in our experiment subjects had additional speed cues since they were given an explicit speed instruction before each trial and drove the vehicle themselves, so all tactical and auditory information was available. The 25 Hz occlusion also had considerable effects, similar to the results of Riemersma [1987] in his field study on visual cues in lateral control. So, although a frequency of 25 Hz would still enable a cognitive evaluation of speed, apparently the 10 ms period of presenting information is too short for properly perceiving rate information directly e.g. by looming detectors as suggested by i.e. Regan and Beverly [1978].

In summary, the following conclusions can be drawn from this study:

- TTC at the onset of braking (TTC_{br}) increases with speed, but less than could be expected from a simple model of using a constant level of required deceleration. At higher speeds higher deceleration levels are needed,
- although all subjects display this strategy of increasing TTC_{br} with speed, the individual differences suggest that different criterion levels are used,
- during the braking process itself, on an average, TTC reaches a minimum level of about 1.1 s (TTC_{min}), that is independent on speed, normal or hard braking instruction, or driving experience,

- stroboscopic occlusion, that excludes the direct perception of TTC information from the optic flow field, substantially deteriorates the performance of both experienced and inexperienced drivers,
- the results of this study support the hypothesis of the direct use of TTC information from the optic flow field for drivers' strategy of braking.

7 GENERAL DISCUSSION

In this chapter the main conclusions of this study will be summarised and discussed (Section 7.1), whereas the relevance for practical applications and directions for future research will be outlined in Section 7.2.

7.1 Discussion of results

The main purpose of this study was to identify what distinguishes normal and critical encounters, and how this relates to road user decision-making in traffic. In particular, the analysis of road user behaviour was focussed on the use of time-based measures, since these combine several dynamic aspects of road user behaviour in encounters with other road users or with the road environment and enable a more general approach to the problem of how one switches among the different hierarchical levels of the driving task (Chapter 2). The initial approach, as applied in this study, was to conduct systematic observations of arbitrary road users in the natural setting of actual traffic situations. A video-based observation and analysis method was developed that enables an objective quantification of dynamic characteristics of road user behaviour in interactions with the road environment or with other road users (Chapter 3). In Chapter 4 it was investigated how road users deal with the road environment in negotiating several types of intersections as such. Apart from the results of the individual studies that could be derived from a time-based analysis of road user behaviour (summarised in Section 4.5), it appears that, at signalised road intersections an equal probability of stopping or non-stopping occurs at a Time-To-Stop-line (TTS) of 4 s at the onset of yellow, whereas at AKI railway grade crossings a probability of stopping of 0.5 is already reached at a TTS of 2.2 s. The greater willingness to stop at railway crossings, however, requires sometimes a very strong deceleration rate of well over 4 m/s^2 and/or a stop very close to the track, and therefore, the decision to stop at a TTS of 2.2 s can be regarded as rather critical. The TTS of 4 s at signalised road intersections is more in line with normal behaviour to be expected to occur. The difference in decision-making at vehicle-actuated and fixed time control systems indicates that motorists have certain expectations about the functioning of the signals and act accordingly.

At non-signalised intersections, the Time-To-Intersection measure (TTI) enables an integral approach to the problem of how road users deal with the negotiation of several types of intersections without (Chapter 4) or with other traffic (Chapter 5). Analysing approaching behaviour in terms of time-based measures such as TTI, provides us with a general time frame, with the help of which the influences of type

of priority regulation or type of intersection lay-out on road user behaviour can be determined. Road users display rather consistent behavioural patterns dependent on the type of intersection that is approached. At a yield intersection, for example, car drivers from the minor road, start braking at a constant TTI of about 4 s away from the intersection (taking one second into account for the time between decision and actual deceleration), a value that, in general, is rather independent of the approach speed, the type of manoeuvre, the type of party on the main road, and the direction the party is coming from. The control of braking appears to be also rather consistently conducted, in that, if a minimum TTI (TTI_{min}) occurs before actually entering the intersection, this minimum is almost always higher than 1.5 s. The occurrence of a TTI_{min} indicates that the driver has enough time available to come to a successful stop, if necessary, and the proportion of approaches with a TTI_{min} may reflect the willingness of a road user to stop. At a yield intersection this type of behaviour is more frequently displayed than at a general rule intersection, and is independent of the type or approach direction of the party on the main road. At the general rule intersection, both the proportion of approaches with a TTI_{min} and the mean TTI_{min} values properly reflect whether one has the right of way or not. At all intersections the moment TTI_{min} occurs, is closely related to the moment of maximum deceleration.

Also head movement patterns appear to be typical for the type of priority regulation that is in force. Contrary to the findings at the yield intersection where motorists preponderantly start looking to the left, at the general rule intersection the presence of a party from the right, directs attention and increases the number of first head movements into the direction of the other party. This increase is not affected by the type of party (bicyclist or car), neither is the moment the first head movement occurs (at a TTI between 2 and 2.7 s).

At intersections with separate bicycle tracks along the main road, a TTI analysis of free-moving motorists approaching from the minor road reveals that drivers' attention is more directed to the main road than to the cycle track. Only special provisions (speed control humps, lane narrowings, deviant pavement colour, and the like), such as applied at intersections of special bicycle routes, address drivers' attention to the cycle track.

In Chapter 5, several studies were used to evaluate the Time-To-Collision (TTC) measure in both normal and critical encounters. In particular, TTC_{min} indicates how imminent an actual collision was during the process of approaching each other. The analysis of all encounters of a given type that occur during a given period, provides us, on the one hand, with data on normal encounters, whereas, on the other, both objective and subjective data on traffic conflicts, as available from the two calibration studies on Traffic Conflicts Techniques, enable us to evaluate more critical encoun-

ters. In general, the encounters scored as conflicts by observer teams in the field, have a much lower TTC_{min} than the normal encounters. For conflicts, the median TTC_{min} value is 1.5 s, whereas encounters hardly display a TTC_{min} less than 1.5 s. Within the group of conflicts as scored by observer teams in the Malmö calibration study, the comparison between objective measures and subjective severity scores reveals that TTC_{min} is a major factor in explaining subjective severity of conflicts. However, it also becomes clear that the relation between TTC_{min} and conflict severity scores is not unambiguous; severe conflicts have a low TTC_{min} , but not all conflicts with a low TTC_{min} are regarded as severe. The evaluation of conflicts that were scored by only one team and of encounters with a close proximity between road users, together with the large differences among the number of conflicts scored by the various teams, clearly demonstrate the detection problems (both 'misses' and 'false alarms') human observers experience in the field, especially at the border-line between slight conflicts and encounters. But once a more serious conflict is detected, the severity is rather consistently evaluated. To conclude, TTC_{min} is an important variable in discriminating between normal and critical encounters, with a distinct detection threshold of 1.5 s. But for evaluating the overall severity of conflicts, observers take also other (subjective) aspects into account, that are difficult to specify. No evidence was found that including acceleration explicitly into the definition of TTC is advantageous; the way TTC_{min} accounts for this (see Appendix B), seems to be sufficient and is more in line with empirical findings on visual perception of motion [Lee et al., 1983; Jagacinski et al., 1983].

Based on the results of Chapter 4 and 5, it was hypothesized that road users make directly use of time-based measures, such as TTC, as a cue for decision-making in traffic. This hypothesis was tested in a field experiment on drivers' decision-making in braking (Chapter 6). Lee [1976] suggested that determining whether one is on a collision course, judging when to start braking, and controlling the braking process itself, can be based on TTC information as directly available from the optic flow field. In our experiment, subjects approaching a stationary object (simulated rear end of a small passenger car) were instructed to start braking at the latest moment they thought they could stop in front of the object. The results reveal that TTC at the onset of braking increases with speed, but less than could be expected from a constant deceleration model. At higher speeds higher deceleration levels are needed. During the braking process itself, TTC reaches a minimum of about 1.1 s, that is independent of speed, normal or hard braking instruction, and driver experience.

Given the instruction to start braking at the latest moment, our data represent absolute minimum values that one obviously wants to avoid in actual traffic. At a speed of 50 km/h (speed limit in urban areas) the hard braking instruction results in

a mean TTC_{br} of 1.6 s. This value corresponds well with the value of 1.5 s that is often used to define serious conflicts [e.g. Hydén, 1984]. Recently, Hydén [1987] proposed a critical threshold value that is increasing with speed. In this respect our hard braking data may well serve as a realistic basis for defining serious conflicts. The normal braking instruction gives a mean TTC_{br} of 2.5 s at a speed of 50 km/h. Again, this value is quite in line with the criterion Hydén uses for defining slight conflicts at that speed. Given the results on the decision to start braking when approaching various types of intersections under normal circumstances, viz. at about 4 s away from the intersection, these values indeed represent rather critical situations one wants to avoid in actual traffic.

The empirical TTC_{min} value of 1.0 s Hayward [1972] suggested for defining serious car-car conflicts is quite in line with our results. It also supports the TTC criteria that are used in the Dutch conflict observation technique DOCTOR [Kraay, Van der Horst and Oppe, 1986] to define traffic conflicts, viz. that, in general, only interactions with a TTC_{min} of less than 1.5 s constitute potentially dangerous situations and that situations with a TTC_{min} of less than 1 s are regarded as serious conflicts.

In general, the results from stroboscopic occlusion, that excludes the direct perception of TTC information from the optic flow field, are more compatible with the optic flow theory than with the competing theory in which observers include distance and speed information explicitly in their judgment. This doesn't imply, however, that other cues are not used at all in actual driving. But why should it be a matter of adopting one method or the other? A combination of information from different sources may be much more attractive and efficient, since it enables the driver to respond to a variety of situations under different circumstances. During normal driving the processing of optic flow field information at the control level of the driving task can be executed almost automatically without much cognitive time demand, and ample time can be spend on other aspects of the driving task. In particular, the detection of an emergency situation, is more likely based on the direct processing of optic flow field information, causing a first (automatic) quick response, and it enables an "interrupt" of other ongoing activities at a higher cognitive level. This mechanism might well be regarded as an implementation of the "emergency relay" in the model of Bötticher and Van der Molen [1988]. But it certainly does not exclude a more cognitive evaluation of the situation after this interrupt has occurred. In this respect we firmly support the conclusion by Cavallo and Laurent (1988) that further research is needed on how and under which circumstances the various kinds of information are complementing each other.

7.2 Applications and future research

First of all, the various observational studies in actual traffic, as used in this dissertation, directly demonstrate the usefulness of analysing road user behaviour in terms of time-based measures for evaluating operational and infrastructural countermeasures to improve efficiency and road safety. Moreover, it may contribute to the further development of intersection design standards in the light of the concept of the 'self-explaining' road, in which geometric road design elements effect desired road user behaviour and no additional enforcement is needed.

Driver support systems based on new technologies

Under the auspices of the Commission of the European Communities, an ambitious research programme DRIVE is currently conducted. In this programme, the potential role that new technologies may play in solving today's and tomorrow's problems in road transportation, are investigated. DRIVE envisages a road transport environment in which drivers are better informed and 'intelligent' vehicles communicate and cooperate with the road infrastructure itself. To define system requirements, detailed information is needed on how drivers operate, what type of information should be provided to the driver, and at what level the system takes over. TTC may prove to be an effective variable, for example, to define operational criteria for collision avoidance systems. Recently, Janssen [1989] started research on this topic.

Driver modelling

The correspondence in the results of the analysis of driver behaviour in terms of time related measures suggests a fundamental relationship with control and decision-making strategies used by drivers in every day traffic. The approach based on time related measures seems promising to provide a framework for modelling driving as a supervisory control task [Blaauw, 1984]. By this approach driving is considered to be a time-management task where time related measures at the different hierarchical levels of the driving task are comparable and may serve as a uniform decision criterion when to switch among subtasks.

Perception of Time-To-Collision

In our experiment drivers' strategy of braking was investigated for the simple situation of approaching a stationary object. A logical next step would be to extend it to situations where the other road user involved is also moving, such as in car-following or in interactions at road intersections. With respect to the latter, Bootsma [1988] claims that time-to-contact between two objects, located anywhere in the field of view, is available in optic variables that can be directly picked up. The constancy of TTC_{min} over speed together with the close relationship between the moment of

maximum deceleration and the moment TTC_{min} occurs, suggests that TTC_{min} is an important variable in controlling the braking process. In Appendix B, it is briefly indicated how this may work. It is worthwhile to continue research on the perception of TTC along these lines, in which the emphasis should be on how and under which circumstances the various kinds of information are complementing each other in actual traffic situations. The logistics for these type of experiments in actual field trials, however, may become very complicated. A more practical approach may be offered by using a driving simulator instead, which also would allow for an extensive manipulation of visual cues as presented to the driver.

The video observation technique

In this study, the video observation technique has proven to be very helpful in analysing road user behaviour in actual traffic. The advantage of using video is, among other things, that only one sensor is needed for measuring several aspects of behaviour in an integrated manner. Moreover, the possibility to select specific events by visual inspection from video, partly bridges the gap between mere observations in the field and laboratory experiments with respect to controllability and validity. However, since the work of the human operator is still time-consuming and strenuous, a further automation is needed. Recently, the development of an automated system for road traffic analysis made a promising start [Szanto, 1987; 1989].

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APPENDIX A

COMPUTATION OF THE COEFFICIENTS FOR THE TRANSFORMATION
FROM VIDEO-IMAGE TO ROAD PLANEMethod

For the transformation from video-image to the road plane, the method of two-dimensional projective coordination (Hallert, 1960) is applied. The transformation of video image coordinates (X_v, Y_v) to road coordinates (X_r, Y_r) is given by a broken linear function of the following form:

$$\text{and } \left. \begin{aligned} X_r &= \frac{C_1 X_v + C_2 Y_v + C_3}{C_7 X_v + C_8 Y_v + 1} \\ Y_r &= \frac{C_4 X_v + C_5 Y_v + C_6}{C_7 X_v + C_8 Y_v + 1} \end{aligned} \right\} \quad (A1)$$

In principle, the coefficients C_1 to C_8 can be calculated if the coordinates of four points are known in both the video-image plane and the road plane.

Basically, the procedure consists of the following steps:

- a) Measuring the mutual distances among the reference points in the road plane,
- b) defining an arbitrary coordinate system (X_r, Y_r) for the road plane and converting the distance information into X_r and Y_r coordinates,
- c) measuring the reference points in the coordinate system (X_v, Y_v) in the video image plane, and
- d) computing the transformation coefficients C_1 to C_8 , based on a set of four reference points.

It is obvious that small errors in measuring the four reference points in the plane of both the road and the video-image may largely influence the accuracy of the transformation. To have a check on the transformation and to be able to conduct an optimisation procedure, some additional reference points are included. A total number of eight to ten points serves well for this purpose. If more than four reference points are available, the following steps are added:

- e) selecting four reference points out of the set of n , to be used as a starting point in
- f) finding the optimal transformation coefficients based on minimising the errors in road coordinates of all reference points in an iterative process.

ad a) The number of distances to be measured is $n(n-1)/2$ with n the total number of reference points. The distances at road level are measured by measuring tape or measuring wheel. In principle, for locating each point relatively to the others it would be sufficient to know the distances to three other points. Nevertheless, redundant information by additional distances is very helpful in detecting occasional measuring errors and enables an optimising procedure in the next step.

ad b) A separate optimising procedure has been developed for converting the distances between the reference points into road coordinates. This step will not be discussed in this context. For more details, the reader is referred to Van der Horst [1990].

ad c) The measurement of the X_v and Y_v coordinates of the reference points in the video image plane is conducted by applying the video plotting device as briefly described in Section 3.2.3. By analysing video stills the resolution in the vertical direction is given by the number of available lines in one video field. Using a system operating under the European PAL standard this number is about 300. In a well-defined video signal about 500 points can be resolved horizontally.

ad d) Substituting the X_r , Y_r , X_v and Y_v coordinates of the four points in Eq. (A1) results in a set of eight linear equations with the X , Y coordinates of the four reference points in both planes as known parameters and C_1 to C_8 as unknown variables. For solving this set of equations a general numerical method is used, known as the Gauss-Lu decomposition technique [Stoer, 1972].

ad e) The selection of the set of four reference points out of all available points (n) consists of a straight forward computation of C_1 to C_8 (according to step d)) for all possible combinations of four points out of all n points ($n!/(n-4)!4!$ steps). The set with the least square error in road coordinates of all reference points is taken as the starting point for step f).

ad f) This optimisation consists of varying the coefficients in such a way that the squared error between a road coordinate as deduced from video coordinates and the actual road coordinate, summed over all reference points, is minimal.

The optimisation problem can be defined as minimising the errors in road coordinates of all reference points resulting in the following objective function:

$$f_{obj} = \sum_{i=1}^n \left\{ \left(X_{ri} - \frac{C_1 \cdot X_{vi} + C_2 \cdot Y_{vi} + C_3}{C_7 \cdot X_{vi} + C_8 \cdot Y_{vi} + 1} \right)^2 + \left(Y_{ri} - \frac{C_4 \cdot X_{vi} + C_5 \cdot Y_{vi} + C_6}{C_7 \cdot X_{vi} + C_8 \cdot Y_{vi} + 1} \right)^2 \right\} \quad (A2)$$

There are two ways of looking at this objective function. The first one is to consider f_{obj} as a function of the variables C_1 to C_8 with all coordinates as known parameters. Another approach might be to optimise this function by allowing small changes in the video coordinates, for example within the resolution of the video plotting system. This may be advantageous when some reference points are located in the far end of the image, where one pixel represents a relatively large distance on the road. Since the coefficients C_1 to C_8 are also a function of the video coordinates the definition of the optimisation problem becomes rather complex.

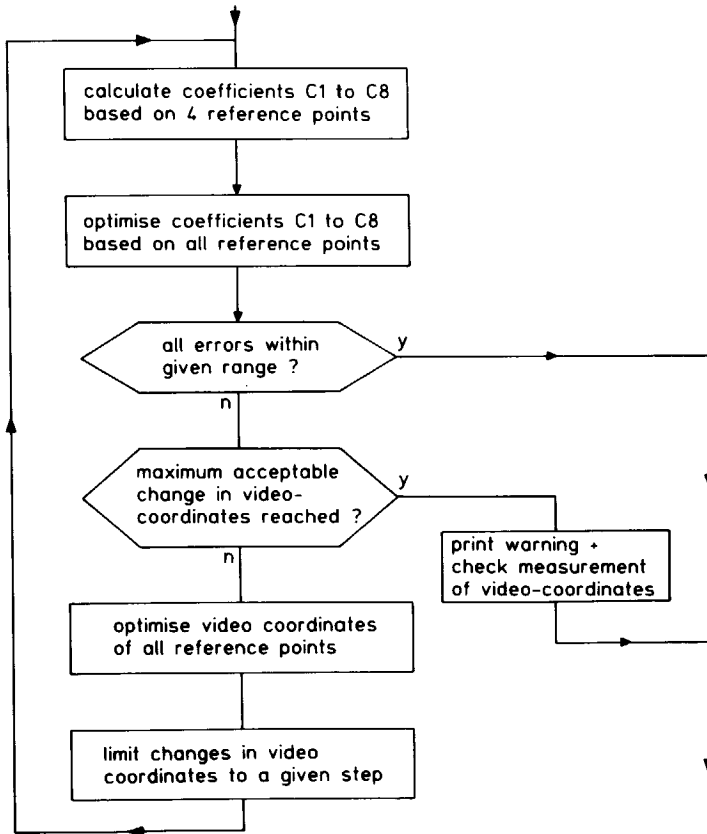


Fig. A1 Flow diagram of optimisation of transformation coefficients.

Therefore, an iterative procedure was developed, in which the coefficients C_1 to C_8 are considered as known parameters during the optimisation of video coordinates, and vice versa, see Fig. A1. It is obvious that the resulting solution, in principle, may consist of relatively large changes in certain video coordinates, while only small changes are permitted. Therefore, only small changes of the video coordinates up to a given size (for example up to 0.5) are implemented and with these marginally modified video coordinates the calculation and optimisation of the eight transformation coefficients is repeated. Eventually, this procedure can be repeated (within a given maximum acceptable change in video coordinates) till a given error criterion has been met (see Fig. A1). For practical reasons a criterion is imposed that each individual transformed reference point must lie within a circle of a given radius (for example 0.05 m) surrounding the actual reference point. For most locations this criterion is met within a one pixel change of one or more video coordinates.

The two optimisation steps, viz. optimising the transformation coefficients C_1 to C_8 and optimising the video coordinates, will now be discussed in some more detail.

The optimisation of the transformation coefficients

Because all partial derivatives of f_{obj} to the variables C_1 to C_8 can be formulated (see Eqs. (A3) through (A10)) a general non-linear optimisation algorithm can be applied [Vaessen, 1984].

$$\frac{d f_{obj}}{d C_1} = \sum_{i=1}^n -2 \cdot A_i \cdot \frac{X_{vi}}{\text{denom}} \quad (\text{A3})$$

$$\frac{d f_{obj}}{d C_2} = \sum_{i=1}^n -2 \cdot A_i \cdot \frac{Y_{vi}}{\text{denom}} \quad (\text{A4})$$

$$\frac{d f_{obj}}{d C_3} = \sum_{i=1}^n -2 \cdot A_i \cdot \frac{1}{\text{denom}} \quad (\text{A5})$$

$$\frac{d f_{obj}}{d C_4} = \sum_{i=1}^n -2 \cdot B_i \cdot \frac{X_{vi}}{\text{denom}} \quad (\text{A6})$$

$$\frac{d f_{obj}}{d C_5} = \sum_{i=1}^n -2 \cdot B_i \cdot \frac{Y_{vi}}{\text{denom}} \quad (\text{A7})$$

$$\frac{d f_{obj}}{d C_6} = \sum_{i=1}^n -2 \cdot B_i \cdot \frac{1}{\text{denom}} \quad (\text{A8})$$

$$\begin{aligned} \frac{d f_{obj}}{d C_7} = \sum_{i=1}^n & \left(2 \cdot A_i \cdot \frac{C_1 \cdot X_{vi} + C_2 \cdot Y_{vi} + C_3}{\text{denom}^2} \cdot X_{vi} + \right. \\ & \left. 2 \cdot B_i \cdot \frac{C_4 \cdot X_{vi} + C_5 \cdot Y_{vi} + C_6}{\text{denom}^2} \cdot X_{vi} \right) \quad (\text{A9}) \end{aligned}$$

$$\frac{d f_{obj}}{d C_8} = \sum_{i=1}^n \left(2 \cdot A_i \cdot \frac{C_1 \cdot X_{vi} + C_2 \cdot Y_{vi} + C_3}{denom^2} \cdot Y_{vi} + 2 \cdot B_i \cdot \frac{C_4 \cdot X_{vi} + C_5 \cdot Y_{vi} + C_6}{denom^2} \cdot Y_{vi} \right) \quad (A10)$$

$$\begin{aligned} \text{with } A_i &= X_{ri} - \frac{C_1 \cdot X_{vi} + C_2 \cdot Y_{vi} + C_3}{denom}, \\ B_i &= Y_{ri} - \frac{C_4 \cdot X_{vi} + C_5 \cdot Y_{vi} + C_6}{denom}, \text{ and} \\ denom &= C_7 \cdot X_{vi} + C_8 \cdot Y_{vi} + 1 \end{aligned}$$

Optimisation of video coordinates

By regarding f_{obj} of Eq. (A2) as a function of the video coordinates the following partial derivatives can be formulated (for $i=1,n$):

$$\begin{aligned} \frac{d f_{obj}}{d X_{vi}} &= -2 \cdot \left(X_{ri} - \frac{numx}{denom} \right) \cdot \left(\frac{C_1 \cdot denom - C_7 \cdot numx}{denom^2} \right) - \\ &2 \cdot \left(Y_{ri} - \frac{numy}{denom} \right) \cdot \left(\frac{C_4 \cdot denom - C_7 \cdot numy}{denom^2} \right) \end{aligned} \quad (A11)$$

and

$$\begin{aligned} \frac{d f_{obj}}{d Y_{vi}} &= -2 \cdot \left(X_{ri} - \frac{numx}{denom} \right) \cdot \left(\frac{C_2 \cdot denom - C_8 \cdot numx}{denom^2} \right) - \\ &2 \cdot \left(Y_{ri} - \frac{numy}{denom} \right) \cdot \left(\frac{C_5 \cdot denom - C_8 \cdot numy}{denom^2} \right) \end{aligned} \quad (A12)$$

$$\begin{aligned} \text{with } numx &= C_1 \cdot X_{vi} + C_2 \cdot Y_{vi} + C_3, \\ numy &= C_4 \cdot X_{vi} + C_5 \cdot Y_{vi} + C_6, \text{ and} \\ denom &= C_7 \cdot X_{vi} + C_8 \cdot Y_{vi} + 1 \end{aligned}$$

Again, the non-linear optimisation algorithm of Vaessen [1984] is used for finding the 'optimal' video coordinates. As stated before, this solution itself is not realistic, but it gives the direction of the marginal changes in the video coordinates that are explored in a next optimisation of transformation coefficients. When a given acceptable error in the positioning of individual reference points is met, the final coefficients C_1 to C_8 are known and can be used for the transformation of arbitrary points from video coordinates to coordinates in the road plane, given by Eq. (A1).

APPENDIX B

COMPUTATION OF TIME-TO-COLLISION

General

After the quantitative measurements from video and the transformation to the road plane, the positions of the vehicles are available in X_r and Y_r coordinates at successive time moments (usually $dt = 0.24$ s), Van der Horst [1982]. From the successive positions the instantaneous speed, acceleration, and heading-angle can be derived. Based on this information i.a. the Time-To-Collision (TTC) measure can be calculated.

Let the situation at a given time $t = T$ be given by Fig. B1.

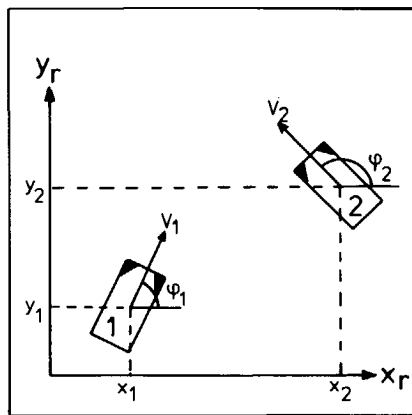


Fig. B1 Situation at $t = T$ with $x_i = X$ -coordinate in the road plane, $y_i = Y$ -coordinate, $v_i =$ speed, $a_i =$ acceleration and $\phi_i =$ heading-angle of vehicle i ($i=1,2$).

Irrespectively of which assumption is made for the continuation of movement from the moment T on, the TTC concept requires always two steps:

- a) detect whether both vehicles have a mutual collision course, and if so,
- b) calculate TTC at moment $t = T$.

When two road users are approaching each other, in general, there will be an area of intersection S , defined by the dimensions of the vehicles. For the simple case of a perpendicular angle of intersection, an example is given in Fig. B2.

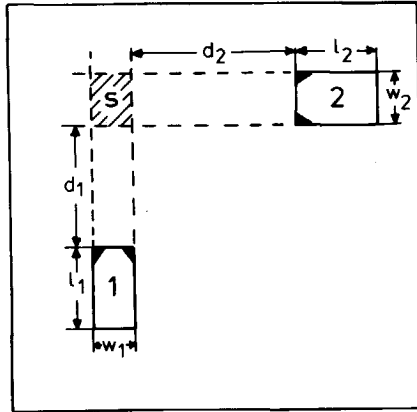


Fig. B2 Situation at $t = T$ for a perpendicular approach with the area of intersection = S , l_i = length, w_i = width of vehicle i ($i=1,2$) and d_i = distance from front of vehicle i to area S .

A collision course will only occur, if one of the following conditions is satisfied:

$$t_{f1} < t_{f2} < t_{r1} \quad (\text{B1})$$

or

$$t_{r2} < t_{f1} < t_{r2} \quad (\text{B2})$$

with t_{f1} , t_{f2} = the moment the front of vehicle 1, vehicle 2, respectively, reaches area S , and
 t_{r1} , t_{r2} = the moment the rear of vehicle 1, vehicle 2, respectively, leaves area S .

If neither Eq. (B1) nor (B2) is satisfied, there is no collision course, and consequently, TTC will be infinite. If Eq. (B1) holds, the TTC value at time $t=T$ is given by:

$$\text{TTC} = t_{f2} - T \quad (\text{B3})$$

while for Eq. (B2) is true:

$$\text{TTC} = t_{f1} - T \quad (\text{B4})$$

Of course, t_{f1} through t_{r2} will depend on the positions, the speeds and the heading-angles at $t = T$, as well as on the assumption of the continuation of movements from moment T on.

TTC based on constant speed and heading-angle

If the continuation of movement is to be defined by a constant remaining speed and heading-angle, the time moments for the example of Fig. B2 are given by:

$$t_{f1} = T + d_1/v_1 \quad (B5)$$

$$t_{r1} = T + (d_1 + l_1 + w_2)/v_1 \quad (B6)$$

$$t_{f2} = T + d_2/v_2 \quad (B7)$$

$$t_{r2} = T + (d_2 + l_2 + w_1)/v_2 \quad (B8)$$

If Eq. (B1) is satisfied, then substituting Eq.(B7) into Eq. (B3) gives:

$$TTC = d_2/v_2 \quad (B9)$$

and, if Eq. (B2) is satisfied, then substituting Eq. (B5) in Eq. (B4) gives:

$$TTC = d_1/v_1 \quad (B10)$$

For non-perpendicular angles of intersection, all corner points of both vehicles have to be considered separately to determine whether a collision course is present or not. Besides, more types of potential collisions have to be taken into account. For an acute angle, for example, six different collision types are possible (Fig. B3) with separate conditions and equations for collision course and calculation of TTC. In addition, both rear-end and head-on approaches require different computations.

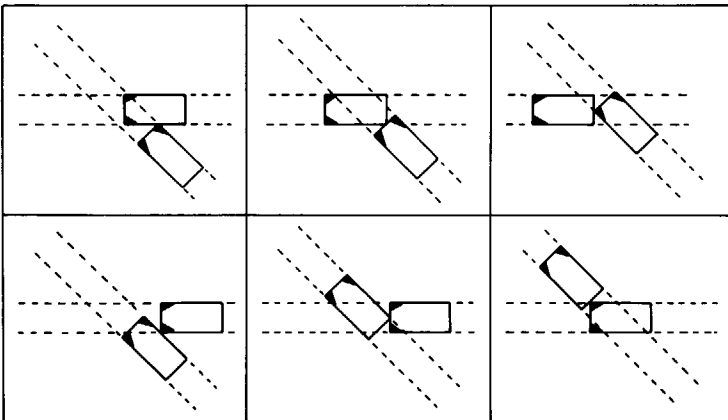


Fig. B3 Types of potential collisions for an acute angle of approach.

TTC based on constant acceleration and heading-angle

When the continuation of movement is based on constant remaining accelerations (or decelerations), also mathematical expressions for t_{r1} through t_{r2} can be derived, with some restrictions dealing with potential stops before or after entering the area S. In the actual computer program, however, a more general approach is followed by using numerical methods for solving a set of higher order equations; both x and y from the moment T on are given as a n^{th} order polynom in t.

Computation of minimum TTC (TTC_{\min})

The minimum TTC as reached during an interaction between two road users with a collision course at a certain moment, is determined by comparing all TTC values that are present in the encounter. So, no separate computation is needed to obtain TTC_{\min} . But to illustrate how TTC_{\min} depends on acceleration, also when a constant continuation of movement is based on constant speed, the simple example of an car approaching an fixed object is discussed. We assume that at time moment $t = 0$ a constant acceleration of $-A$ m/s^2 is instantaneously in effect. For a movement with a uniform acceleration, the following Eqs. hold:

$$\text{acceleration: } a = -A \quad (\text{B11})$$

$$\text{speed: } v = v_0 + a.t \quad (\text{B12})$$

$$\text{distance travelled: } d = v_0.t + 0.5.a.t^2 \quad (\text{B13})$$

The TTC at moment t is given by:

$$TTC = (d_0 - d) / v \quad (\text{B14})$$

Substituting Eqs. (B2) and B(3) in Eq. (B14), gives:

$$TTC = (d_0 - v_0.t - 0.5.a.t^2)/(v_0 + a.t) \quad (\text{B15})$$

The moment the minimum of TTC is reached (t_{\min}), is determined by the derivative of TTC equals zero:

$$d/dt(TTC) = 0, \text{ or}$$

$$\{(v_0 + a.t).(-v_0 - a.t) - (d_0 - v_0.t - 0.5.a.t^2)\}/(v_0 + a.t)^2 = 0$$

resulting in:

$$0.5.a^2.t^2 + a.v_0.t + v_0^2 + d_0.a = 0 \quad (\text{B16})$$

The condition of no collision is only valid if both Eqs. (B17) and (B18) are satisfied, i.e.:

$$-a \geq v_0^2 / (2.d_0) \quad (\text{B17})$$

and

$$t < -a/v_0 \quad (\text{B18})$$

resulting in:

$$t_{\min} = -v_0/a + (-v_0^2 - 2.d_0.a)^{1/2}/a \quad (\text{B19})$$

Substituting $t = t_{\min}$ in (B15) gives:

$$\text{TTC}_{\min} = (d_0 - v_0.t_{\min} - 0.5.a.t_{\min}^2) / (v_0 + a.t_{\min}) \quad (\text{B20})$$

In Eq. (B20), TTC_{\min} is given as a function of the acceleration a and the distance and speed at moment $t = 0$. But TTC_{\min} can also be expressed as a function of the speed and distance at moment $t = t_{\min}$, viz.:

$$\text{TTC}_{\min} = d_{\min} / v_{\min} \quad (\text{B21})$$

Since it can easily be derived, that d_{\min} also equals $-v_{\min}^2 / a$, Eq. (B21) results in:

$$\text{TTC}_{\min} = -v_{\min} / a \quad (\text{B22})$$

The time it takes to come to a stop from moment t_{\min} on, also equals to $-v_{\min} / a$. This implies that at t_{\min} , TTC_{\min} is equal to the time it takes from the current moment on, to come to a complete stop. From this, a simple decision rule may be derived, viz. if TTC is less than the remaining stopping time, continue braking. After TTC reached its minimum, TTC will be greater than the remaining stopping time, implying that the deceleration may decrease. Since the moment of maximum deceleration appears to be closely related to the moment TTC_{\min} occurs, it may well be that drivers' strategy is based on an estimate of the stopping time, which would enable the simple task of comparing TTC and the remaining stopping time. Further elaboration of this hypothesis, however, will be needed.

LIST OF SYMBOLS

a	acceleration	m/s ²
ACC	acceleration	m/s ²
ACC _{min}	minimum acceleration (maximum deceleration) as reached during the braking process	m/s ²
ACC _{req}	average required acceleration to come to a successful stop	m/s ²
ACC _{tmin}	acceleration at the moment of minimum TTI	m/s ²
C ₁ -C _B	coefficients of the transformation from video image plane to road plane	
d	distance travelled	m
D _{max}	maximum difference between two cumulative distributions	
DIM1	PRINCALS severity score of conflicts from subset 1 (conflicts from the Malmö calibration study scored by four or more teams)	
DIM2	PRINCALS severity score based on analysis of total set of conflicts from the Malmö calibration study	
DIM3	PRINCALS severity score of the conflicts from the Trautenfels study	
DIST	distance to intersection or object	m
DIST _{br}	distance to intersection or object at the onset of braking	m
DIST _{stp}	distance to object after vehicle has stopped	m
DIST _{tmin}	distance to intersection at t _{min}	m
DIST _{1st}	distance to intersection at the moment of the first head movement	m
DTS	<u>signalised road intersections</u> : the distance a given road user is away from the stop-line at the onset of the yellow signal <u>railway grade crossings</u> : the distance a given road user is away from the first track at the onset of the flashing red signal	m
DTTC	distance between two road users involved in an interaction at the moment of TTC _{min}	m
P _L	party from the left	
P _R	party from the right	
PET	Post-Encroachment-Time	s
t _{ACCmin}	moment of ACC _{min}	s
t _{dif}	t _{ACCmin} minus either t _{min} or t _{TTCmin}	s
t _{min}	moment of TTI _{min}	s
t _r	reaction time of road user	s
t _{TTCmin}	moment of TTC _{min}	s
TA	Time-To-Accident	s
TLC	Time-to-Line-Crossing	s

TPS	<u>signalised road intersections</u> : time of passing the stop-line after the onset of the yellow signal <u>railway grade crossings</u> : time of passing the first track after the onset of the flashing red signal	s
TTC	Time-To-Collision	s
TTC_{br}	TTC at the onset of braking	s
TTC_{min}	minimum TTC	s
TTCA	Time-To-Collision with continuation of movement based on constancy of acceleration and of heading angle	s
TTI	Time-To-Intersection	s
TTI_{br}	TTI at the onset of braking	s
TTI_{min}	minimum TTI	s
TTI_{1st}	TTI at the moment of the first head movement	s
TTS	<u>signalised road intersections</u> : the time a given road user is away from the stop-line at the onset of the yellow signal <u>railway grade crossings</u> : the time a given road user is away from the first track at the onset of the flashing red signal	m
V	speed	m/s
V_{br}	speed at the onset of braking	m/s
V_{tmin}	speed at t_{min}	m/s
V_{1st}	speed at the moment of the first head movement	m/s
X_r	x-coordinate of the road plane	m
X_v	x-coordinate of the video image plane	
Y_r	y-coordinate of the road plane	m
Y_v	y-coordinate of the video image plane	

EEN ANALYSE VAN HET GEDRAG VAN WEGGEBRUIKERS IN NORMALE EN KRITISCHE ONTMOETINGEN GEBASEERD OP TIJDMATEN

SAMENVATTING

In het huidige verkeer treden de beperkingen aan de menselijke mogelijkheden tot het verwerken van informatie steeds duidelijker naar voren. Vooral op kruispunten vragen diverse delen van de rijtaak tegelijkertijd de aandacht. Om de verkeersveiligheid te kunnen verbeteren, is het van groot belang om inzicht te krijgen in hoe weggebruikers omgaan met complexe situaties, zoals het naderen en passeren van kruispunten, en welke informatie zij nodig hebben om juiste beslissingen te kunnen nemen. Het analyseren van kritische ontmoetingen (bijna-ongevallen of verkeersconflicten) biedt niet alleen de mogelijkheid om meer inzicht te verkrijgen in de processen die uiteindelijk resulteren in een ongeval, maar kan ons eveneens meer kennis verschaffen over hoe weggebruikers in staat zijn een kritische situatie om te zetten in een beheersbare. Het doel van de huidige studie is om na te gaan wat normale van kritische ontmoetingen onderscheidt en hoe dit in relatie staat tot het nemen van beslissingen in het verkeer. Voor het analyseren van het gedrag van weggebruikers in het werkelijke verkeer is een op video gebaseerde observatie- en analysemethode ontwikkeld die het mogelijk maakt om dynamische kenmerken van gedrag in ontmoetingen met andere weggebruikers of met de wegomgeving objectief te bepalen.

Onderzocht is hoe het naderen en passeren van verschillende typen kruispunten zonder en met ander verkeer aanwezig, in zijn werk gaat. Het beslissen van automobilisten op met verkeerslichten geregelde kruispunten en op AKI spoorwegovergangen bij respectievelijk het aangaan van het gele licht of het knipperend rood is geëvalueerd in termen van Time-To-Stop-line (TTS). Bij spoorwegovergangen is de bereidheid om te stoppen veel groter dan bij kruispunten met verkeerslichten; op kruispunten besluit de helft van de automobilisten die op een TTS van 4 s van het kruispunt af zijn, om te stoppen (normaal gedrag), terwijl bij spoorwegovergangen deze kans op stoppen al bereikt wordt bij een TTS van 2.2 s. Het besluit om te stoppen op een moment dat men al zo dicht de overweg genaderd is, leidt echter soms tot een kritische situatie. Een verbetering van de signalering bij spoorwegovergangen lijkt goed mogelijk.

Voor niet met verkeerslichten geregelde kruispunten verschaft de Time-To-Intersection (TTI) maat een algemeen tijdraam voor het naderingsproces, met behulp waarvan de invloed van het type voorrangregeling of kruispuntvormgeving op het gedrag van weggebruikers kan worden bepaald. Afhankelijk van het type voorrangregeling, vertonen weggebruikers een tamelijk consistent naderingspatroon. Op een voorrang-

kruispunt bijvoorbeeld, beginnen automobilisten met remmen op een TTI van ca. 4 s. Als er een minimum TTI optreedt voordat men de kruising oprijdt, gebeurt het afremmen zodanig dat dit minimum in het algemeen boven de 1.5 s blijft. Ook bij ontmoetingen met verkeer op de hoofdweg wordt een vergelijkbaar gedrag vertoond, dat onafhankelijk is van het soort partner en zijn naderingsrichting. Op een kruispunt waar de algemene voorrangsregeling van toepassing is, blijkt zowel het aandeel naderingen met een TTI_{min} als de gemiddelde TTI_{min} waarde goed aan te geven of men voorrang heeft. Hoofdbewegingspatronen blijken eveneens typerend voor het soort voorrangsregeling dat geldt. Automobilisten die een voorrangskruispunt vanaf de zijweg naderen, kijken overwegend eerst naar links, terwijl op een gewoon kruispunt de aanwezigheid van een van rechts komende partner, de aandacht trekt en het aantal eerste hoofdbewegingen in de richting van die partner doet toenemen. Een TTI analyse van het naderingsgedrag op kruispunten met afzonderlijke fietspaden langs de hoofdweg laat zien, dat de aandacht van automobilisten meer gericht is op de hoofdweg dan op het fietspad. Speciale maatregelen, zoals verkeersdrempels, insnoeringen, afwijkende kleur van het fietspadwegdek, e.d., zijn nodig om de aandacht meer te richten op het fietspad.

Diverse studies werden gebruikt om de Time-To-Collision (TTC) maat te evalueren voor zowel normale als kritische ontmoetingen tussen weggebruikers. In het bijzonder geeft de TTC_{min} aan hoe dreigend een daadwerkelijke botsing is geweest tijdens het naderingsproces. Verreweg de meeste ontmoetingen vertonen nauwelijks een TTC_{min} kleiner dan 1.5 s, terwijl voor ontmoetingen die door observatorteams als conflict zijn gescoord tijdens twee internationale calibratiestudies van verkeersconflictechnieken, de mediaanwaarde 1.5 s bedraagt. Een vergelijking tussen objectieve maten en subjectieve ernstscores laat zien dat TTC_{min} een belangrijke factor is voor het verklaren van de subjectieve ernst van conflicten. Observatoren betrekken echter ook andere (subjectieve) aspecten bij hun ernstoordeel die moeilijk zijn te specificeren. Bovendien blijkt uit een analyse van conflicten die maar door één team zijn gescoord en van ontmoetingen waarbij de betrokken weggebruikers elkaar dicht naderen, alsmede uit de grote verschillen in het aantal conflicten gescoord door de verschillende teams, dat observatoren met name in het grensgebied tussen lichte conflicten en ontmoetingen problemen hebben met de detectie van relevante situaties. Maar als eenmaal een wat ernstiger conflict is gedetecteerd, dan wordt de ernst tamelijk consistent beoordeeld. TTC_{min} blijkt een belangrijke variabele bij het onderscheiden van normale en kritische ontmoetingen met een kenmerkende drempelwaarde van 1.5 s. Er zijn geen aanwijzingen gevonden dat een definitie van TTC waarin versnelling expliciet is opgenomen, voordelen biedt; de wijze waarop versnelling een rol speelt bij het tot stand komen van TTC_{min} , lijkt voldoende.

De resultaten van de observatiestudies in het werkelijke verkeer, wijzen op het directe gebruik van tijdmaten, zoals bijv. TTC, door weggebruikers bij het nemen van allerlei beslissingen in het verkeer. Om deze hypothese te toetsen is een veldexperiment uitgevoerd, waarbij proefpersonen de opdracht kregen om, terwijl ze met een bepaalde snelheid een stilstaand object (de gesimuleerde achterkant van een personenauto) naderden, te remmen op het laatste moment dat ze dachten net vóór het object tot stilstand te kunnen komen. De resultaten laten zien dat TTC op het moment van remmen weliswaar toeneemt met de snelheid, maar minder dan op grond van een model met een constante benodigde remvertraging kon worden verwacht. Bij hogere snelheden zijn grotere remvertragingen noodzakelijk. Bij een snelheid van 50 km/h en een instructie om hard te remmen, begint men te remmen bij een TTC van 1.6 s. De minimum TTC die tijdens het afremmen optreedt, bereikt een minimum waarde van ca. 1.1 s, die onafhankelijk is van snelheid, instructie om normaal of hard te remmen, en rijervaring. De gevonden waarden zijn goed in overeenstemming met empirische bevindingen bij onderzoek naar verkeersconflictechnieken. Stroboscopische occlusie, waarmee de directe waarneming van TTC informatie uit het visuele stroomveld onmogelijk gemaakt wordt, verslechtert de prestatie van ervaren en onervaren bestuurders aanzienlijk, zowel t.a.v. de beslissing om te gaan remmen als bij het afremproces zelf. Deze resultaten zijn meer in lijn met de 'optic flow' theorie dan met de veronderstelling dat bestuurders afstand- en snelheidsinformatie afzonderlijk betrekken in hun oordeel.

De overeenkomsten in de resultaten van een op tijdmaten gebaseerde analyse van het gedrag van weggebruikers suggereren dat tijdmaten een directe rol spelen bij de regel- en beslissingsstrategieën van weggebruikers in het dagelijkse verkeer. De benadering gebaseerd op tijdmaten biedt een algemeen kader voor het op integrale wijze modelleren van de verschillende hiërarchische niveaus van de rijtaak. De resultaten demonstreren de praktische waarde van deze benadering bij het evalueren van operationele en infrastructurale maatregelen ter bevordering van verkeersafwikkeling en verkeersveiligheid.

A TIME-BASED ANALYSIS OF ROAD USER BEHAVIOUR IN NORMAL AND CRITICAL ENCOUNTERS

SUMMARY

In modern road traffic the limitations of human information processing capabilities become increasingly apparent. Especially at intersections, the three levels of the task of the road user, viz. navigation, guidance and control, are often competing. To improve traffic safety it is of utmost importance to collect basic knowledge on how road users deal with complex situations such as negotiating intersections, and which information they need for proper decision-making. Analysing road user behaviour in critical encounters (near-misses or traffic conflicts) 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. The main purpose of the present study is to identify what distinguishes normal and critical encounters, and how this is related to road user decision-making. To reach this goal, the present analysis of road user behaviour is focussed on the use of time-based measures since these combine several dynamic aspects in encounters with other road users or with the road environment. A video-based observation- and analysis-method was developed that enables an objective quantification of dynamic characteristics of road user behaviour in various traffic situations.

The approach chosen in this study, was firstly to investigate how road users deal with negotiating several types of intersections, both with and without the presence of other traffic. At both signalised road intersections and railway grade crossings drivers' decision-making in relation to the onset of the yellow or the flashing red signal, respectively, was evaluated in terms of Time-To-Stop-line (TTS). At railway grade crossings, the willingness to stop is much greater than at road intersections; at road intersections, half of the drivers at a TTS of 4 s away from the intersection decide to stop (normal behaviour), whereas at railway grade crossings this probability of stopping is already reached at a TTS of 2.2 s. However, deciding to stop when one is that close to the tracks, sometimes results in critical situations. A revision of the signalisation at railway grade crossings is suggested.

At non-signalised intersections, the Time-To-Intersection measure (TTI) provides us with a general time frame, with the help of which the influence of type of priority regulation or type of intersection lay-out on road user behaviour can be determined. Road users display rather consistent behavioural patterns dependent on the type of priority regulation. At a yield intersection, for example, car drivers from the minor road, start braking at a TTI of about 4 s away from the intersection. In general, the

control of braking is conducted in such a way that, if a minimum TTI occurs before actually entering the intersection, this minimum is higher than 1.5 s. Also in interactions with traffic on the main road a similar type of behaviour is displayed, that is independent of the type of party on the main road and the direction the party is coming from. At a general rule intersection, both the proportions of approaches with a TTI_{min} and the mean TTI_{min} values properly reflect whether one has the right of way or not. Also head movement patterns appear to be typical for the type of priority that is in force. At the yield intersection, car drivers preponderantly start looking to the left, whereas at the general rule intersection the presence of a party from the right, directs attention and increases the number of first head movements into the direction of the party on the main road. At intersections with separate bicycle tracks along the main road, a TTI analysis reveals that the attention of drivers approaching from the minor road is more directed to the main road than to the cycle track. Only special provisions (speed control humps, lane-narrowings, deviant pavement colour, and the like) address drivers' attention to the cycle track.

Several studies were used to evaluate the Time-To-Collision measure (TTC) in both normal and critical encounters between road users. In particular, TTC_{min} indicates how imminent an actual collision was during the process of approaching each other. Normal encounters hardly display a TTC_{min} of less than 1.5 s, whereas encounters scored as conflicts by observer teams in the field during two international calibration studies on Traffic Conflicts Techniques, have a median TTC_{min} value of 1.5 s. A comparison between objective measures and subjective severity scores reveals that TTC_{min} is a major factor in explaining subjective severity of conflicts. However, for evaluating the overall severity of conflicts, observers take also other (subjective) aspects into account, that are difficult to specify. Moreover, the analysis of conflicts that were scored by only one team and of encounters with a close proximity between the road users involved, together with the large differences among the number of conflicts scored by the various teams, clearly demonstrates the detection problems human observers experience in the field, especially at the border-line between slight conflicts and encounters. But once a more serious conflict is detected, the severity is evaluated rather consistently. TTC_{min} is an important variable in discriminating between normal and critical encounters, with a distinct detection threshold of 1.5 s. No evidence was found that including acceleration explicitly into the definition of TTC is advantageous; the manner TTC_{min} accounts for acceleration seems to be appropriate.

Based on the results from the observational studies in actual traffic, it was hypothesized that road users make directly use of time-based measures, such as TTC, as a cue for decision-making in traffic. This hypothesis was tested in a field experiment on

drivers' decision-making in braking. Subjects approaching a stationary object (simulated rear end of a car) at a given speed were instructed to start braking at the latest moment they thought they could stop in front of the object. The results reveal that TTC at the onset of braking increases with speed, but less than could be expected from a constant deceleration model. At higher speeds higher deceleration levels are needed. At a speed of 50 km/h, the onset of braking starts at a TTC of 1.6 s (hard braking instruction). During the braking process, TTC reaches a minimum of about 1.1 s, that is rather independent of speed, normal or hard braking instruction, and driver experience. These experimental data are in line with several empirical findings in research on Traffic Conflicts Techniques. Excluding the direct perception of TTC information from the optic flow field by stroboscopic occlusion, substantially deteriorates the performance of experienced and inexperienced drivers in both the decision to start braking and the control of the braking process itself. These results are more compatible with the optic flow theory than with the competing theory in which subjects include distance and speed information explicitly in their judgment.

The correspondence in the results of the time-based analysis of road user behaviour in various situations suggests a fundamental relationship between time measures and road users' control and decision-making strategies in every day traffic. The approach based on time related measures may provide a general framework for modelling the different hierarchical levels of the driving task in an integrated manner. The results also demonstrate its practical value in evaluating operational and infrastructural counter-measures for efficiency and road safety improvement.

CURRICULUM VITAE

Richard van der Horst was born in 1949 at Rotterdam. After graduation at the Sint Franciscus College (Gymnasium-beta) in 1967, he completed a master's degree in electrical engineering at the Delft Technical University in 1973. At the Automatic Traffic Systems Laboratory of the Delft Technical University he did some theoretical work on the optimal setting of traffic control signals after which he went to the TNO Institute for Perception to performing his military services in 1974. Since 1975 he has been with the Traffic Behaviour Research Group of the TNO Institute for Perception as a project leader for human factors research in road traffic. His research includes the development of traffic conflicts techniques, the evaluation of traffic safety measures, and research on human decision-making processes in relation to road environment and other road users. In 1988 he spent a year in Canada conducting experimental research at the Department of Civil Engineering of the University of British Columbia.