DISTANCE BEHAVIOUR ON MOTORWAYS WITH REGARD TO ACTIVE SAFETY – A COMPARISON BETWEEN ADAPTIVE-CRUISE-CONTROL (ACC) AND DRIVER

Björn Filzek

Bert Breuer

Automotive Engineering Department

Darmstadt University of Technology

Germany

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ABSTRACT

Present and future assisting systems are meant to support the driver in coping with the difficulties of driving. The design of the system properties and their limits helps to influence on the road-driving behaviour directly and through teach-back effects. On the other hand there is a potential risk of negative effects on the safety due to a division of tasks between the driver and the technical system. Bearing this in mind, the Automotive Engineering Department and the Department of Ergonomics of Darmstadt University of Technology were engaged by BMW AG to investigate the distance behaviour of vehicles with and without ACC (Adaptive Cruise Control) which is used to control the speed and distance maintained to vehicles ahead and turning into the traffic.

This trial was made with the aim of a representative and objective investigation of the behaviour of the total system of driver-vehicle-environment in road traffic. A total of 50 rides were made on select routes which were carefully analysed with regard to relevant characteristics such as road type, number of lanes and speed limits. In order to avoid any acclimatization problems the testing persons were familiar with the used vehicle type and were selected on the basis of typical distribution of age and mileage travelled. Special emphasis was put on an even distribution of driving experience with and without conventional cruise control. In addition to the video equipment necessary for recording the traffic situation, the test vehicle was fitted with extensive equipment to record the actions of the driver, the driving parameters and distances and speeds relative to the road users ahead.

The complexity of traffic situations necessitated classification in advance. The classification with regard to comparable situations was made, for instance, by means of videos which, in connection with the vehicle data, also served to define the characteristic moments of time and relevant parameters.

On this basis an objective analysis of distance behaviour is made from the safety aspect. The comparison drawn between the actually set and the specified distances reveals the conflict of aims between the compliance with legal regulations and actual traffic conditions. The driver’s behaviour, shaped by their personal motivation differs from the characteristics of the system. Potential methods are sketched out for improving traffic safety by using ACC.

INTRODUCTION

Improvement of traffic safety has always been the aim of vehicle developers. The requirements have drastically increased with rising speeds and traffic. First improvements were made especially in the field of passive safety [6]. Developments such as airbag, belt pretensioners, energy-absorbing body structures and more rigid passenger cells resulted in reduced numbers of injured persons and traffic fatalities despite increasing traffic and accident rates [9]. Through this connection it is clearly possible to see what potentials for improvement could result from accident avoidance.

Today, the progress in sensor technology and the significant increase of performance in signal processing open up advanced possibilities of supporting the driver in the field of active safety [1]. They result in complex technical systems such as vehicle-dynamics-control that has already furnished impressive proof of its effectiveness. Besides the stabilizing systems, which are mainly active in the background, the Active Cruise Control (ACC) is now on the market. Delegating some of the driver´s functions, this system controls the speed and distance to the vehicles ahead and turning into the traffic [10]. Relief of the driver from increasingly complex driving tasks is the professed intention of ACC.

The first generation of headway distance controls only allows for the presetting of distance between vehicles. Nowadays efforts are made to offer an

higher degree of flexibility considering the wide variety of potential traffic situations resulting from the driver´s interaction with other road users [8].
The interaction between the driver and ACC plays the key role. The design of the system is defined by the human requirements, technical feasibility but also by legal restrictions and normal traffic conditions. The criteria of comfort and safety are the main factors in this field of interrelations. They are a decisive factor in defining the benefits obtained through the use of ACC and the possible negative effects resulting from a new distribution of tasks between the driver and the technical system.
This provided the setting for the investigation into distance behaviour on motorways with and without the use of ACC by the Automotive Engineering Department and the Department of Ergonomics of Darmstadt University of Technology according to an order placed by BMW AG. Test drives made by representative persons in road traffic were meant to provide information about the influence of situational and human factors on the distance behaviour and how to define interdependences in an appropriate way.

TEST CONCEPT

Experimental tests under real conditions lead one to expect a natural variety of situations. Two test cycles were defined in which the same driver operated a vehicle with and without using the ACC. In the first phase, a prototype of ACC was used in the background so that the distance to different cars ahead could be measured. The second test phase was centred around the use of the ACC that is produced in series by BMW in the meantime [10]. The test track described hereafter was extended by a starting-up stage to enable the driver to get familiar with the ACC.

Test Track

The test track was designed to achieve representative traffic and driving situations. The pragmatic approach was aimed to cover a great variety of situations. This method was justified in particular by the fact that the test drives should be assessed only situationally, i.e. in small sections with comparable general conditions. Contrary to an existing and accurately analysed test track mostly including country road sections [3], a track mainly including motorway sections was required for testing the ACC as the conventional cruise control is normally used on this type of roads. The test track formed a circuit of 229 km beginning at Darmstadt University of Technology (Figure 1). The characteristics such as routing of the track, number of lanes, speed limit and traffic load were varied on the best possible level.

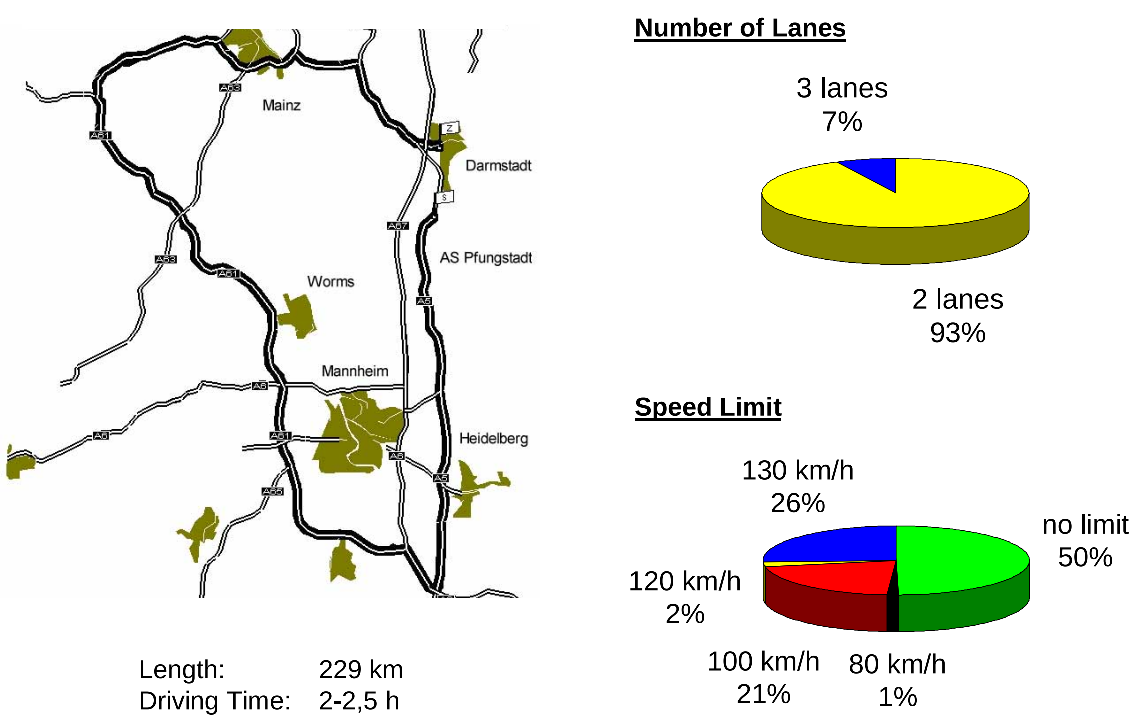

Figure 1. Routing and characteristics of the test track.

Driver group

A representative group of drivers was selected on the basis of a random selection of people from all walks of life. The basic entity was formed by potential users of the system and typical drivers of the type of vehicle under test. In this way it was possible to exclude disturbances caused by habituation to the vehicle. The classification of test persons according to the criteria of age and driving experience is given in Table 1.

Table 1.
Age and driving experience of the test persons

Age [a] / Driving Experience [km]	< 40	40-60	> 60	∑
< 500.000	4	1	1	6
500.000 - 1.000.000	2	5	4	11
> 1.000.000	0	10	2	12
∑	6	16	7	29

Special importance was attached to an even distribution with regard to driving experience with the conventional cruise control.

Besides the selection criteria, individual capacities of the drivers such as personality and motivation are important because they have a strong influence on driving behaviour [4]. These data were collected before and after the drive on the basis of questionnaires and tests.

METHODOLOGY

Figure 2 provides a summary of the necessary working steps from the data acquisition up to analysis.
Classification of the situation is the core of analysis. The complexity and randomness of the road traffic system requires the classification of situations as a prerequisite to structure actual driving activities according to comparable conditions [5]. It is necessary to define criteria for a clear specification of the beginning and the end of a given situation. In this way it is also possible to divide a test drive into different sections that can be evaluated individually and compared among themselves. Finally it is possible to apply these results to other drives independently of their combination.
Here the term “situation“ defines in the first instance the variable interrelation with other road users. The traffic ahead in the same lane is of great interest with

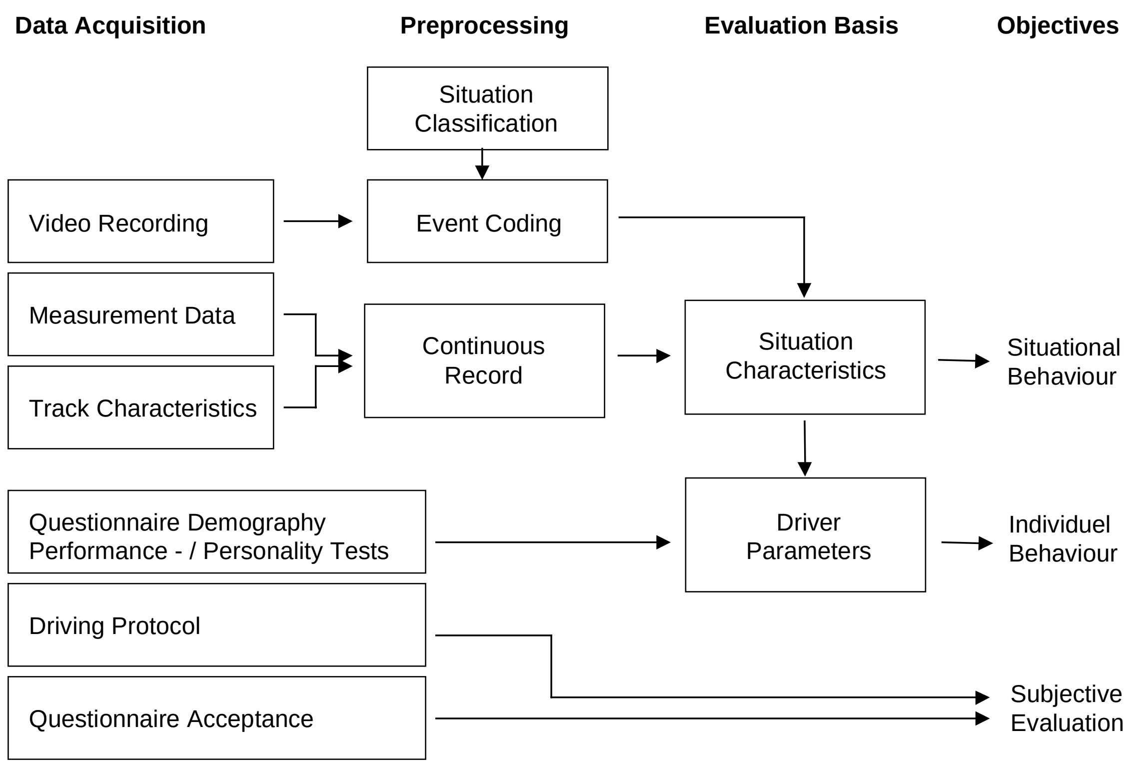

Figure 2. Summary of the working steps necessary for evaluation

regard to ACC. One distinguishes between a “clear run” that is identified by free choice of speed and “restricted run” during which the vehicle ahead sets the pace. The distance between vehicles is decisive in these cases. Following the preceding vehicle the distance remains practically constant therefore necessitating only a small amount of intervention by the driver or ACC.

A comparatively high emphasis is put on the dynamic alterations as here an immediate recognition of changes in a situation plays a major role in coping with it. We talk about the transitions between clear and restricted runs. Transition to restricted run requires adjustment of the driving speed and distance to the preceding vehicle by appropriate deceleration. Following behind is ended when the driving speed is no longer influenced by the vehicle ahead in the same lane and the driver is able to accelerate his car as he wishes.

The distance to the preceding vehicle is a criterion for the identification of free or restricted road driving. Alterations in the situation can happen in different ways and can be retraced to different occurances. Steady alteration in the distance between vehicles indicate different speeds of two cars driving in the same lane. These situations can be defined by the terms of “approach” and “drop back”. Intermittent alterations in the distance between vehicles result from lane changing by either vehicle. Lane changes by other cars are called “turning in” and “turning out” which specifies their relation to the test driver. Lane changes by the test vehicle are named as such. For simplification and because they are very short lane changes, turning in and out are defined as timeless occurrences. A time is allocated at which the vehicle touches the marking strips for the first time. Table 2 shows the classification of the situations.

The behaviour of road users, the causes and consequences can, however, not only be evaluated on the basis of measuring data because not all relevant information can be recorded automatically. Videos of the traffic situation from the driver´s point of view help to close this gap. Depending on the situation manual after-processing must be done on the basis of flowcharts containing the relevant characteristics and the theoretical development of the processes in the form of alternative actions. Finally an overall file containing all the necessary moments of time, parameters and situation characteristics is achieved by synchronization of the time curves of the video and measured data acquisition. This overall file forms the basis of any further evaluation.

Table 2.
Classification of situations

Status	Situation
Free	Clear run
Restricted	Following
Free=>Restricted	Approach
	Turning in
	Lane change
Restricted=>Free	Drop back
	Turning out
	Lane change
Restricted=>Restricted	Turning in
	Turning out
	Lane change

RESULTS

Apart from driving without hindrance ahead the majority of driving time on motorways is occupied by following other vehicles. This status is characterized by relatively constant speeds and distances which change rather slowly. The alterations of speed become slightly more dynamic when approaching a slower vehicle or when the preceding vehicle speeds up. These situations can be recognized at an early stage and can be settled easily. While ones own lane change is pre-planned those initiated by the other drivers are sudden and hard to foresee. The intention usually becomes apparent at the very moment in which it begins. There is no doubt about the fact that the turning-in of a slower vehicle into traffic is the most crucial occurrence. The risk is on a higher level because collision is inevitable should no action be taken. In addition, the available reaction time is significantly smaller than in other situations.

The situation of following another vehicle has the biggest number of time shares and “turning in” is the most demanding situation for the driver and ACC. Therefore these two situations will be in the focus of further considerations.

Follow-up driving

Follow-up driving is mainly characterized by a vehicle driving ahead in the same lane. The driver is forced to follow the preceding vehicle at the same speed. In the ideal case assessment is made on the

basis of settled condition, i.e. the distance between vehicles remains unaltered for a longer period of time. Therefore a narrow range of ±3 km/h is set for the speed relative to the preceding vehicle. Unwanted influences, e.g. caused by acceleration prior to the recognized intention of turning out can be eliminated in this way. Distances between vehicles may be reduced in a similar way when the driver changes lane in order to overtake the vehicle ahead. Such conditions were avoided as the investigation considered only follow-up driving on the outermost left lane. Normally the right-hand lane is only used if the flow of traffic allows speed to be maintained or if other road users are to be given the possibility to overtake. In any case, driving on inside lanes does not represent the typical follow-up driving as defined.
The complexity of factors influencing the driver´s behaviour necessitated a limitation of the assessment to motorways with two lanes because it is assumed that additional lanes will only influence the distance behaviour in exceptional cases. Further limitations refer to the speed that must be above 60 kilometres per hour to exclude conditions similar to a traffic jam and the range of the radar sensor which is limited to 150 meters. The latter is considered as sufficient in the assessed speed range.
According to the preconditions mentioned above Figure 3 shows the temporal frequency distribution of the time gaps, the quotient from distance and speed, for the total number of drivers.

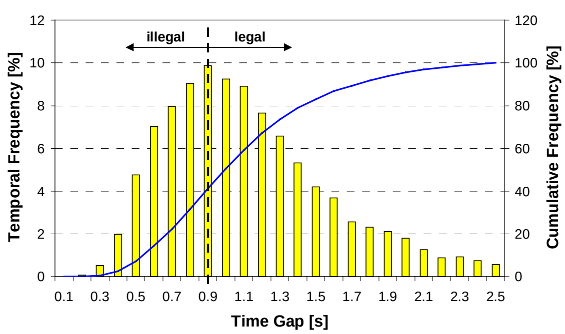

Figure 3. Temporal frequency distribution and cumulative frequency of time gap during following

The Gaussian distribution to be expected in theory leans slightly to the right. This is due to the fact that despite all limitations there are still sections in which a vehicle travelling at some distance ahead was incidentally followed at the same speed without actual control of this distance. However, the drivers fall below the minimum distance of 0.9 seconds as required by German law [2] in 41% of the total time.

Modern ACC Systems offer, on the contrary, time gaps between 1-2 seconds.
The question must be raised as to why drivers take such a safety risk. The trips were not made in a hurry but in a relaxed atmosphere. The presence of the test attendant and the fact that it was a test drive under supervision should rather have resulted in more moderate behaviour than in unusually short distances between vehicles provoked by the driver. It also remains to be clarified why the measured time gaps cover such a wide range. Influence by the driver could be excluded in this connection. Even though the mean values of the individual drivers are in the range between 0.7 and 1.6 seconds, the individual distribution was similar to that of the overall evaluation. This resulted in the assumption that there was another situational influence and subsequent investigation of the influence exerted by the other road users was conducted. For this purpose, the distance data of the preceding vehicles were used to generate a parameter representing the traffic density in vehicles per kilometre. The calculated values are always related to the total in both lanes.
Figure 4 represents the distance to the preceding vehicle related to defined traffic density and speed.

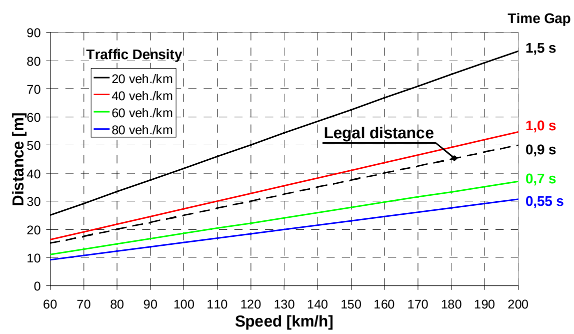

Figure 4. Distance and time gap during following related to speed and traffic density

The curves result from a regression calculation based on the total of measuring points that are not shown here for reasons of clarity. The standard deviation amounts 10.5 meters resp. 0.3 seconds reflecting the time gap.
The regression gives a clear insight into the interrelationships. At first it is confirmed that the distance behaviour is linear versus speed and that the time gap is a suitable form of representation. All regression lines start close to the origin. The influence of traffic density, however, is superimposed on the speed. The defined time gap is reduced when more vehicles travel in the range up to the preceding vehicle in the driver’s lane. The time gap is 1.5 seconds in the case of a rather small traffic densities of 20 vehicles per kilometre. Larger traffic densities

reduce the time gap and values above 45 vehicles per kilometre result in time gaps below the minimum value of 0.9 seconds which would be required according to german law. Differences between the drivers are excluded but show, however, an individual influence on the shifting and twisting of the regression line for different traffic densities.

Turning-in

The initial phase of a turning-in situation is characterized by another car changing lane and moving into the test driver´s lane. In the case of slower vehicles, which will be evaluated here, this causes a reaction on the part of the driver. In the given cases it is not possible for the driver to change his own lane to pass the vehicle, he therefore has to reduce the speed of his vehicle to that of the vehicle turning in. Normally the situation is ended in this way. Should the vehicle turn out again, or another vehicle turn in or the driver change his lane the situation has to be unconsidered. The adaptation of distance and speed to the turned in vehicle ahead must be included in a model in order to compare it with the ACC characteristics and in the long run to derive a target.

In order to assess the time schedule concerning the turning-in situation one first has to define the beginning and end of reaction time. Under normal circumstances, i.e. in settled condition, the turning-in situation is preceded by a constant speed that is freely selected or defined by a vehicle already being ahead at this time. In both these instances no mentionable acceleration or deceleration is necessary. A slower vehicle will, however, definitely initiate deceleration the beginning of which is clearly shown by the negative acceleration curve.

The aim of the beginning of the deceleration process is to adapt ones own speed to that of the preceding vehicle. In consequence, the time at which the relative speed between the two vehicles is zero is best suited to define the end of the reaction. At this precise moment the distance between vehicles is at a minimum because the driver although he normally drops back a little will maintain the current distance. This distance will hereafter be referred to as “minimum distance“. Thus the time limits, in which the changes in distance between vehicles can be described, are defined and a coherent representation of the characteristics of turning-in can be produced.

The behaviour of ACC and driver will hereafter be compared by means of models representing the beginning of deceleration and minimum distance.

Beginning of deceleration has been defined as the time at which the first rear axle tire of the turning-in vehicle crosses the track line. Figure 5 shows the model of deceleration beginning for the driver and ACC. The example represents a speed of 165 km/h. Each curve represents another relative speed.

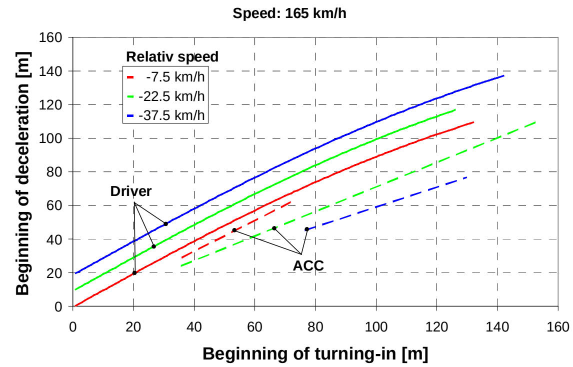

Figure 5. Comparison of the beginning of deceleration of driver and ACC versus beginning of turning-in and relative speed

Whereas the behaviour of the ACC is characterized nearly exactly the curves of the driver characteristics specify the beginning of deceleration with a max. error of 20% related to 80% of the situations. Interindividual and intraindividual differences between the drivers remain unconsidered at present and are discussed in [7].

The curves representing the driver and ACC differ in their appearance already. With the driver, the beginning of deceleration is degressive to the beginning of turning-in. When there is only a small distance between vehicles deceleration is started immediately the vehicle in front begins to turn in. Therefore the curve shows ascent 1 in the lower range. The curve does not need to start at the origin because the definition of the starting point of turning-in is certainly not recognized in the same way by all drivers. With larger distances in the beginning of turning-in, the beginning of deceleration is always asymptotic versus a fixed distance value as the starting point of turning-in does not play a role anymore.

On the other hand the ACC behaviour can be described by straight lines the ascent of which, however, represent the relevant curve of the driver quite well. The absolute difference between driver and ACC is negligible at small relative speeds. Deviations are not more than a few metres and are constant versus the beginning of turning-in. The curves start drifting apart with increasing relative speed and are on different levels. While the reaction of ACC is more and more delayed, the driver is increasingly aware.

The driver´s anticipation is explained by the definition of the beginning of turning-in which was first made under the assumption that the defined moment must be objective and repeatable. However, even small changes of the position of the other vehicle in its lane may already make the test driver alert to the turning-in procedure. The probability is additionally increased when, for instance, the other vehicle runs up to a vehicle ahead of it. In this way the probability of turning-in results from the situation and different influences which in total form the driver´s subjective appraisal and will make him decelerate the vehicle from a certain point. Turning in at higher relative speeds cannot be expected to result in an earlier recognition of the situation. In fact, the desired degree of safety will reduce the reaction threshold of the driver so that he will start the deceleration process sooner.

Not only will the driver recognize the intention of turning in earlier but he also will initiate the deceleration of this own car at an earlier time. The limited ability of the ACC to clearly realize the turning-in situation causes a delay. This time of verification results in a reduction of the distances at increasing relative speed at which deceleration can be started. For this reason, the system is more and more overdriven with increasing relative speed. All those interventions were early enough and done in a controlled manner without causing any critical situation.

Minimum distance - Neither the driver nor the ACC show any influence of the driving speed on the chosen minimum distance, however, there is an interdependence with regard to the relative speed. Starting with low relative speeds Figure 6 shows that ACC sets slightly bigger minimum distances at comparable beginning of deceleration.

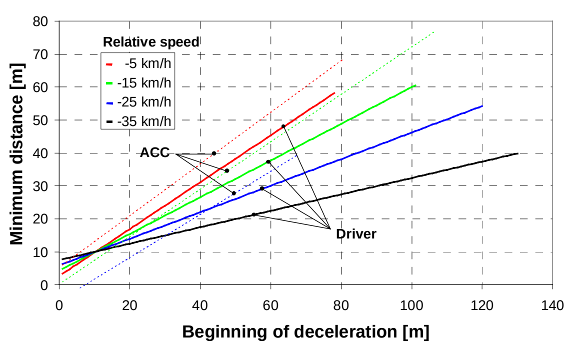

Figure 6. Comparison of minimum distances kept by the driver and ACC versus beginning of deceleration and relative speed

Higher relative speeds result in smaller distances with both the driver and the ACC. The regression lines of ACC are shifted almost in parallel so that the minimum distance is reduced independently to the beginning of deceleration. On the other hand, the curves of the driver are twisted versus relative speed and change their gradient versus the beginning of deceleration. In connection with an early beginning of deceleration there are significantly smaller distances kept by the driver especially in the case of high relative speeds. This might not only be caused by comfort-oriented deceleration but also by the driver´s motivation to anticipate or even provoke certain reactions by the preceding road user.

At this point we do not want to give the impression that the driver will always select the smaller distance in comparable situations. The situation is reciprocal when including the kept distances to the beginning of the turning-in process. As explained above, the driver starts to decelerate earlier, i.e. at bigger distance values and in consequence reaches bigger minimum distances.

CONCLUSION

Two situations that are characterized by a significant difference with regard to the frequency and potential risk clearly show the difference in the distance behaviour of driver and ACC. There are many and varied reasons for the differing system characteristics.

The applied time gaps mirror the conflict of aims between the compliance with legal regulations and actual traffic conditions. The drivers set significantly smaller distances than are allowed by legislation because the traffic density plays a major role. Vehicles in the right-hand lane are potential turning-in ones and their increasing number also increases the probability that they will fill the gap to the preceding vehicle. In order to prevent getting behind the drivers increasingly reduce the distance. Today's traffic volume necessitates situations that are contrary to legal regulations. For this reason it is hard to design ACC that is likewise in compliance with law and acceptable to the user.

A second aspect is given by the different capabilities of man and machine. Besides preferences provided by technology the diversity of human characteristics and adaptability of the driver also remain as positive factors. They enable him to anticipate the situation which makes him react to increasing relative speed much earlier than is possible by today´s ACC.

In addition to different response there are other differences between the driver and ACC regarding the activity that shall not remain unmentioned. ACC is limited to reactions that will be identical in identical environmental conditions. The driver, however, will change his behaviour according to his motives. The measuring data prove that the distances set in connection with a vehicle turning in are very often reduced significantly. The driver does not

decelerate the vehicle as expected but sometimes even accelerates in an attempt to hinder another driver from turning in, to make him turn out or to maintain the speed of his own vehicle in the case of anticipated turn-out of another vehicle.
There are undoubtedly different approaches to positively influencing the distance behaviour by using ACC. The capabilities of man and machine can best be exploited in a combined system. In this regard the modelled driver behaviour helps to assess the characteristics of ACC and further promote their acceptability.

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