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A SIMULATOR EVALUATION OF DIFFERENT FORMS OF INTELLIGENT CRUISE CONTROL

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J.H. Hogema, A.R.A. van der Horst, and W.H. Janssen

SUMMARY

Intelligent Cruise Controls (ICCs) are currently in development and will become commercially available within a few years. An ICC is an in-vehicle system that partially takes over the longitudinal driving task: it regulates a vehicle's speed and it is also capable of maintaining a proper following distance behind a lead car. Combining an ICC with a communication system from the roadside to the vehicle offers the possibility to obtain in-car preview information about relevant conditions on the road ahead. An ICC could even adjust automatically to that situation without intervention of the driver.

This report describes an experiment which was carried out in the TNO driving simulator to compare driving behaviour under ICC combined with several forms of in-vehicle information. The information which was sent to the vehicle was concerned with local speed limits and their rationale. The ICCs studied varied in the way this information was used: informative (leaving it to the driver whether to adjust his speed) or intervening (i.e. making the ICC automatically obey the speed limit). Also the way in which the information was presented to drivers was varied: in addition to a basic configuration, visual, acoustic, or haptic feedback could be given. Driving with one specific system configuration, subjects were confronted with a number of critical scenarios.

The behavioral measurements taken were related to the two modes of ICC, i.e. the regulation of one's own speed and the regulation of following distance. As expected, an ICC results in a reduced proportion of small time headways. With regard to speed choice it was found that only the intervening systems results in a speed reduction on sections with a special speed limit. However, there seems to be a compensating mechanism in that actively reducing a driver's speed on a few limited sections makes him drive faster on other parts.

It also appeared that the combination of ICC with in-vehicle information resulted in a somewhat later braking reaction of the driver in situations the ICC could not cope with. Effects of feedback type were not found, possibly because of the redundancy of the in-vehicle information, or because the basic feedback configuration is sufficiently informative. In the current experiment, subjects had to keep their foot on the gas pedal to keep the ICC active; this was done both as a safety measure and to enable the use of haptic feedback by means of the gas

pedal. Several disadvantages of this approach were found: a considerable proportion of the subjects gave a negative judgement about this aspect and the results show that some difficulties occurred in the operation of the system.

The conclusion is drawn that the combination of ICC with different forms of in-vehicle information appears to show specific effects on driver behaviour, not all of them being favourable. A number of suggestions for relevant further research is presented.

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TNO Technische Menskunde[1]
Soesterberg

Een simulator-evaluatie van verschillende vormen van Intelligent Cruise Control

J.H. Hogema, A.R.A. van der Horst en W.H. Janssen

SAMENVATTING

Intelligent Cruise Controls (ICCs) zijn momenteel in ontwikkeling en zullen binnen enkele jaren commercieel verkrijgbaar zijn. Een ICC is een voertuigsysteem dat de longitudinale rijtaak gedeeltelijk van de bestuurder overneemt: het regelt de snelheid van het voertuig en is bovendien in staat om een passende volgafstand achter een voorligger te handhaven. Door een ICC te combineren met een communicatiesysteem van de wegkant naar het voertuig is het mogelijk om in het voertuig informatie te krijgen over relevante condities verderop op de weg. Een ICC zou zich zelfs automatisch aan die situatie kunnen aanpassen zonder tussenkomst van de bestuurder.

In dit rapport wordt een simulatorexperiment beschreven dat is uitgevoerd in de TNO rijsimulator om het rijgedrag bij ICC met verschillende vormen van informatie binnen het voertuig te vergelijken. De informatie die naar het voertuig werd overgestuurd had betrekking op een lokale snelheidslimiet en de reden daarvoor. De onderzochte ICCs varieerden in de wijze waarop deze informatie werd gebruikt: informerend (waarbij het aan de bestuurder werd overgelaten of hij de snelheid aanpaste) of ingrijpend (waarbij de ICC automatisch aan de snelheidslimiet gehoorzaamde). Ook de wijze waarop de informatie aan de bestuurders werd aangeboden is gevarieerd: aan een basis-configuratie kon visuele, akoestisch, of haptische terugkoppeling worden toegevoegd. Rijdend met een specifieke systeemconfiguratie werden de proefpersonen geconfronteerd met een aantal kritische scenario's.

De beschouwde gedragsmaten waren gerelateerd aan de twee toestanden van ICC, namelijk regeling van de eigen snelheid en regeling van volgafstand. Zoals verwacht resulteerde ICC in een afname van de proportie van korte volgtijden. Met betrekking tot snelheidskeuze bleek dat alleen de ingrijpende systemen resulteren in een extra snelheidsafname op de secties met een speciale snelheidslimiet. Er bleek echter een compenserend mechanisme aanwezig te zijn: door de snelheid van een bestuurder op enkele beperkte secties actief te beperken gaat hij harder rijden op andere delen. Verder is gebleken dat de combinatie van ICC met informatie in het voertuig resulteerde in een iets verlate reactie van de

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bestuurder in situaties die de ICC niet meer aankan. Effecten van het soort terugkoppeling zijn niet gevonden, wellicht vanwege de redundantie van de informatie binnen het voertuig, of omdat de basis-uitvoering al voldoende duidelijk was. In het huidige experiment moesten proefpersonen hun voet op het gas houden om de ICC actief te houden; dit werd zowel gedaan uit veiligheidsoverwegingen als om haptische feedback via het gaspedaal mogelijk te maken. Er zijn verschillende nadelen van deze aanpak geconstateerd: een aanzienlijk deel van de proefpersonen gaf een negatief oordeel over dit aspect en de resultaten laten zien dat er wat problemen optraden bij de bediening van het systeem.

Er wordt geconcludeerd dat de combinatie van ICC met verschillende vormen van informatie in het voertuig aanleiding blijkt te geven tot specifieke, deels niet-beoogde effecten op het rijgedrag. Er worden enkele suggesties gedaan voor relevant vervolgonderzoek.

1 INTRODUCTION

The application of advanced technology on the road finds itself in the stage where control over the longitudinal aspects of the driving task comes into sight. This comprises support for regulating the own driving speed and its variability, as well as for regulating certain parameters of car-following performance. Support systems that cover all these elements simultaneously will replace the simple speed-regulating cruise controls that we know today. These new systems are commonly indicated as Intelligent Cruise Controls (ICCs), reflecting the intention to cover more than just simple speed control. Much effort is put into the development of Autonomous Intelligent Cruise Controls (AICCs) that operate without communication with other vehicles or with the roadside. For example, within the PROMETHEUS CED 5 framework a number of AICCs has actually reached demonstrator or prototype status. Such systems, capable of regulating both speed and following distance, essentially take over the longitudinal control part of the driving task. This changes the role of the driver from controlling (i.e. in the loop) to monitoring the ICC's functioning (i.e. out of the loop). Only in situations the ICC cannot cope with, the driver has to take over control again. Possible advantages of such a system are an improvement of driving comfort, and also of safety since the ICC maintains a safe distance. A possible drawback is that using the ICC could reduce the driver's alertness, which may have a negative impact on safety, especially in the relatively rare critical situations where he has to take over control.

To our knowledge the only study that has empirically compared different candidate AICCs is the one by Becker and Sonntag (1993). These authors compared a Daimler-Benz AICC with an Opel 'demonstrator' AICC in real traffic. Both AICCs were quite similar in their control logic as well as in their Man Machine Interface (MMI). These AICCs were truly autonomous, i.e. without communication from the roadside. Results showed that the acceptance was high: the subjects, who had no previous experience with AICC, judged very positively about the driving comfort provided by the AICC. As a possible disadvantage a reduction of alertness is mentioned, especially as a long-term effect.

Also in the area of telematics developments with possible applications in traffic are taking place. For instance, it would be possible to install a communication system capable of sending information from the roadside to the vehicle. This could provide in-vehicle preview information, for instance in the form of a local speed limit. Such information could be altered dynamically, based on relevant conditions on the road ahead, such as the traffic or weather situation. Possible advantages are improvements of traffic flow and traffic safety.

New possibilities arise when ICC is integrated with a communication system. Such a combined system could be constrained to be purely informative, leaving all action to the driver. However, it could also automatically use a maximum speed received from the roadside in the ICC. It could suggest and initiate overrulable actions itself, or it could initiate non-overrulable actions.

Under contract with the Ministry of Transport, Public Works, and Water Management, the TNO Human Factors Research Institute has carried out an empirical study to compare a number of such ICCs combined with in-vehicle information in terms of their effects on driver behaviour. The main questions were how the in-vehicle information should be presented to the driver, and what the effects are of purely informative vs. actively intervening systems. This is a quite new research subject, and therefore the study has an explorative nature. In order to have full control over the experimental conditions, the study has been carried out in the TNO driving simulator.

2 METHOD

2.1 **Experimental conditions and scenarios**

For the externally driven ICCs studied in this experiment the communication assumed is that data are transmitted from the roadside to the vehicle by beacons positioned at specific locations. These data consist, specifically, of the prevailing local speed limit and, when applicable, a rationale for the speed limitation. Once these data are available in the vehicle they may be used in different ways. In the present experiment, two approaches have been compared. The first was to only *inform* the driver of the speed limit, and leave it to him whether to adjust his speed. The second approach consisted in an *intervening* system in which the speed limit was passed on to the ICC system, which then automatically sets a lower speed. An intervention was always accompanied by a message to inform the driver of the prevailing speed limit and/or its rationale. Nevertheless, if the driver wants, he can always drive faster by either overruling the ICC or by switching it off.

When introducing such ICCs in practice, the situation where only a certain proportion of all vehicles is equipped with ICC will occur, and under those circumstances, roadside information will have to remain present beside the communication link. Therefore, in the current study, in-vehicle information was always given in addition to roadside information.

Many options are conceivable to provide the driver with *feedback* on a new speed limit, both in connection with purely informative and with intervening systems. The feedback method can range in complexity from simply informing the driver that a new speed limit has been received to more refined forms in which the driver is also informed of the value of the new limit and/or its rationale. When using a visual display, a straightforward method is to indicate the speed limit on the speedometer, for instance by means of a flashing LED (in contrast to the continuous LED that is commonly used to indicate the driver-set speed). A more sophisticated display could show both the speed limit and its rationale in the form of a pictogram. Acoustic feedback could also be applied, ranging in complexity from a simple buzzer to a spoken message. Finally, haptic feedback could be provided by means of an active gas pedal. These methods all have specific advantages and disadvantages (Lerner et al., 1993). Acoustic and haptic messages, for instance, are temporal in nature. Information on visual displays provide continuously available information, but require the driver to shift visual attention from the traffic scene to the display.

Numerous combinations are possible, but in order to keep the experiment manageable the selection listed in Table I was made. In order to avoid transfer effects, a between-subjects design was used: subjects drove with only a single candidate ICC.

Table I ICC configurations (experimental groups).

Without roadside-vehicle communication	
control group	1
independent ICC	2

With roadside-vehicle communication		
FEEDBACK TYPE	ICC MODE	
	informative	intervening
basic	3	7
visual	4	8
acoustic	5	9
haptic	6	10

In the first two configurations (groups 1 and 2) there was no roadside-vehicle communication, so that these subjects only obtained information directly from the outside world. The first group was the control group in which subjects had no ICC at all. In group 2 an ICC was present, which is referred to as 'independent ICC' because of the absence of a communication link.

In candidate ICCs that included roadside-vehicle communication, two *ICC modes* are distinguished, i.e. an informative and an intervening mode. There were, moreover, four different *feedback types*. The basic configuration was a simple acoustic signal ('beep') which indicated that a new speed had been received from a beacon, in combination with a continuously flashing LED on the speedometer indicating that speed. The remaining three types had an additional feedback

message added to this basic configuration. The visual feedback consisted in standard traffic signs being displayed to the driver on a small colour monitor, indicating both the speed limit and its rationale (for example: "maximum speed 80 km/h" sign and "sharp curve to the right" sign). The acoustic feedback consisted in a spoken message informing the driver of the new speed limit and its rationale (for example: "speed limit 80, sharp curve to the right"). Finally, the haptic feedback consisted in a short vibration on the gas pedal, supported by an acoustic explanation (for example, "sharp curve to the right"). If the driver switched the ICC off altogether, the relevant information nevertheless remained available.
A detailed description of all messages in the separate support conditions is given in Appendix B.

The experimental runs were composed mainly of normal driving situations without a special speed limit or extreme manoeuvres of the other traffic. Every now and then, a subject would be confronted with a critical scenario in which a certain maximum speed applied. Because it would be unrealistic to confront subjects with too many critical scenarios within a short period of time, the following selection was made:

- a 100 km/h speed limit for no apparent reason,
- a 80 km/h speed limit because of a sharp curve in the road, and
- a 50 km/h speed limit because of a traffic queue.

To these more or less critical scenarios was added the 'standard' or 'normal' scenario of driving on a 120 km/h motorway.

The roadside information was given on Variable Message Signs (VMSs) above the road. In all scenarios but the 'standard' one, the VMSs showed maximum speeds signs and when applicable also a sign stating the rationale for the speed restriction (i.e., 'curve' and 'queue'). On the 'standard' road sections the standard motorway speed limit of 120 km/h was not explicitly indicated by traffic signs or feedback messages. This is in correspondence with the functioning of the Dutch Motorway Control and Signalling System which is being implemented in the Netherlands on a large scale (Rijkswaterstaat, 1992). Likewise, the 'intervening' candidate ICCs as designed in this experiment did not actually limit the speed to 120 km/h on these sections, i.e., the driver was free to set the speed he wanted.

Turning now to the car-following mode of the ICCs it should be noticed that ICCs have only a limited range of accelerations and decelerations. This mode is usually meant for increased comfort, and not for dealing with emergency-like situations. For example, in the distance control mode the ICC used in the present experiment only produced accelerations up to 1.2 m/s^2 and decelerations up to 1.8 m/s^2 (in accordance with the Daimler-Benz AICC). Thus, because of its restricted braking rate an ICC is not able to cope with a much slower lead car or hard braking manoeuvres of a lead car. In these cases the driver has to take over control. This is a critical situation that may occur every now and then. With this in mind the 'traffic queue' scenario was in fact designed in such a way that the deceleration required to avoid a collision exceeded the maximum deceleration produced by the ICC. In this way the driver would be forced to take some form of action if he wanted to avoid a collision, and what he does may be of the utmost relevance to the functioning of an ICC as a whole.

Each subject was confronted twice with all scenarios, once in a *free-driving* situation (without leading cars) and once in a *car-following* situation. The other traffic normally obeyed the speed limits. However, it seemed also interesting to investigate how subjects respond when their lead cars ignore the speed limit. Therefore, in one out of the three scenarios in which the subject was following, the lead cars did not obey the speed limit. This took always place in either the 'curve' or the '100 km/h' critical scenarios. The remaining critical scenario (approaching a queue) forced leading vehicles to decelerate at all occasions, so that there could not be the variation on the 'obedience' dimension. Obedience was varied between subjects.

2.2 **Apparatus**

The TNO driving simulator

The experiment was conducted in the driving simulator of the TNO Institute for Human Factors, which is described in detail by Van der Horst, Janssen and Hoekstra (1991). It consists of the following four subsystems.

- The *supervisor* computer (PC, 80486 microprocessor, 33 MHz clock frequency), which has as its tasks the communication with both the experimenter and the other subsystems, the control and monitoring of the experiment, data storage, controlling the behaviour of other traffic, etc. In the present experiment the supervisor also computed the control algorithm of the ICC.
- The *vehicle model* computer (PC, 80486 microprocessor), which calculates the momentaneous position (X-, Y-, and FI-coordinates) of the simulated vehicle; this vehicle has the dynamic characteristics of a Volvo 240.
- The *ICC interface computer*, which realizes the Man-Machine Interface of the cruise control. It reads the ICC switches controlled by the driver, and also controls the additional feedback to the driver (visual, acoustic and haptic).
- The *Computer Generated Image* system (CGI, Evans & Sutherland ESIG 2000), which generates real-time images (refresh frequency 60 Hz, update frequency 30 Hz).

During experiments, the subject is seated in a fixed base mock-up of a Volvo 240 and has all normal controls (steering wheel, accelerator, brake, etc.) at his disposal. Based on the control signals, the vehicle model computes the momentaneous state of the vehicle model. An elaborate description of this model is given by Godthelp, Blaauw and Van der Horst (1982). Feedback of steering forces is given to the driver by means of an electrical torque engine, and of sound by an electronic sound generator (noise of engine, wind, and tires). The momentaneous position (X, Y) and heading angle (FI) are transmitted via the supervisor to the visual scene computer. The CGI system computes the visual scene as seen from the position of driver. This image is projected on a screen in front of the mock-up by means of a high-resolution BARCOGRAPHICS 800 projector (visual angles: 50° horizontally, 35° vertically). The experimenter is seated in a room next to the mock-up room, where he has access to the control system. Communication with the subject is possible by means of an intercom.

The logic of the Intelligent Cruise Control

The control logic of the ICCs implemented for the present experiment was largely based on the Daimler-Benz approach to AICC as described by Müller and Nöcker (1992). As explained before, in the absence of a leading vehicle the ICC provides *speed control*. In this case the control loop aims to keep the actual speed of the vehicle equal to the reference speed set by the driver. If a lead vehicle is detected the ICC switches automatically to *distance control*. In this mode the following distance is controlled at an appropriate value (in the current experiment a time headway of 1.5 s).

There are three ICC states to be distinguished: 'on and not overruled', 'on but overruled', and 'off'. In the 'on and not overruled' state, the ICC is controlling the car's speed. There are situations possible where the driver wants to drive faster than the ICC-regulated speed for a short period of time, for instance during a take-over manoeuvre. This can be achieved by pressing the gas pedal firmly, causing the ICC to switch to the 'on but overruled' state in which the gas pedal position produced by the driver determines the car's speed, but the ICC algorithm is still running in the background. (If the driver wants to drive at a higher speed for a longer period, he would typically do this by increasing the ICC's set speed, not by overruling the ICC.) If the driver sufficiently releases the gas pedal the ICC will automatically return to the 'on and not overruled' state.
When the driver wants to reduce speed in the 'on and not overruled' state, he can do so by adjusting the ICC's set speed or by switching the ICC 'off'. Once the ICC is 'off', the ICC algorithm is terminated altogether and it can only be re-engaged by an action of the driver. This is an essential difference with the 'on but overruled' state. In this report the term 'overrule' will only be used to indicate the situation where the driver exceeds the ICC's speed by pressing the gas pedal.

The ICC can be switched on and off by means of the *ICC switch* attached to the steering column (see Fig. 1). Its *set* function switches the ICC on and takes the current speed as the reference (set) speed. After the ICC has been disengaged, the *resume* function can also be used to switch the ICC on: then the earlier set speed is used again. Once the ICC is on, the driver can adjust the set speed in two ways. The *accelerate/decelerate* function of the ICC switch gradually increases or decreases the set speed, whereas the *speed select pushbutton* (Fig. 1)

can be used to increase or decrease the set speed in steps of 10 km/h. The set speed is displayed in multiples of 10 km/h by a continuous LED on the speedometer.
When a lead vehicle has been detected, a five-segment LED bar on the dashboard gives an indication of the distance to the lead car: red LEDs mean that the distance is too small, an orange LED means the distance is normal, and green LEDs indicate too large a distance (with respect to the 1.5 s headway setpoint).

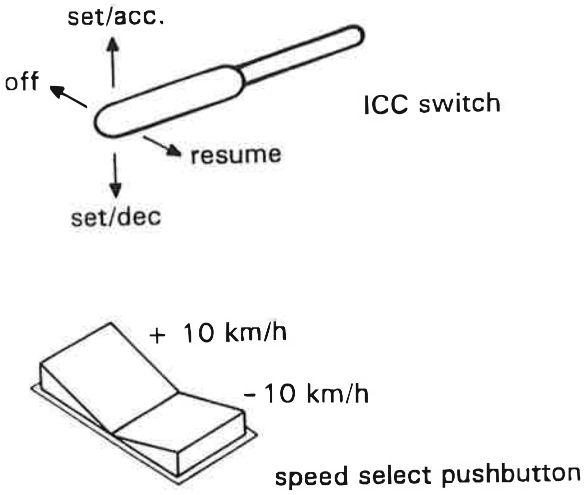

Fig. 1 Control switches of the ICC.

There is one major difference between the Daimler-Benz AICC and the ICCs used in this study. The Daimler-Benz AICC allows the driver to take his foot off the gas pedal when the ICC is active. The ICCs used in the present experiment only functioned as long as the subject kept his foot on the gas pedal: releasing the gas pedal automatically switched the ICC off. This was done as a safety measure, preventing the driver from having to search for the brake pedal in case of an emergency. In addition, haptic feedback by means of the active gas pedal would simply not be possible if the driver did not have his foot on the pedal. The subject could overrule the ICC at all times by pushing the gas pedal deeper than 80% of the full range.

For a detailed technical description of the ICC, the reader is referred to Appendix A.

2.3 **Subjects**

Sixty male subjects participated in the experiment. They all had a driving licence for at least three years and they drove at least 10 000 km a year. Their age ranged from 21 to 54 (mean 37.1, standard deviation 8.4 years). Fifty-four subjects had earlier experience with the driving simulator; these were assigned at random to an experimental group. The remaining six subjects were each assigned to a different experimental group. The subjects were paid for their participation.

2.4 **Procedure**

Before the first experimental run each subject was verbally given general instructions. He was informed that he would be driving on a motorway and that everyday traffic situations would be encountered. Subjects were asked to drive as they normally would in their own car.

Each subject completed two blocks that both consisted of two experimental runs. Each separate run took approximately twenty minutes. The first block consisted of two control runs, i.e. without the support of an ICC or communication system. All combinations of the three critical scenarios and free-driving/car-following conditions occurred once in this block; in one out of the three car-following scenario's, the lead cars disobeyed the speed limit. Information in the control runs was only available from the projected images of the outside world.

After the control block the experimenter gave operating instructions for the specific form of ICC the subject would be using. The experimenter first verbally explained how to operate the ICC and what kind of feedback the subject would receive. It was explicitly stated that the ICC is no anti-collision system that is capable of dealing with emergency situations. Subjects were instructed to use the ICC as much as possible and to disengage it only when they considered this really necessary. After the instruction was completed a training run was started, during which the experimenter was seated on the passenger seat of the mock-up and made sure that the subject would encounter and use all ICC functions at least once. After the training session there was the second block of two runs with the appropriate ICC, that was identical in structure to the preceding control block.

Each separate run was started on the right lane at almost standstill. The subject then would accelerate to his desired speed. During the rest of the run he would be confronted with the four scenarios as described before, viz. the traffic queue, the sharp curve, the 100 km/h section, and the standard sections. Several kilometres before the onset of each separate scenario, either one or two lead cars appeared on the road. Initially these were positioned standing on the hard shoulder. When the distance to these cars became less than 450 m, they accelerated with 2 m/s^2 to a speed 30 km/h lower than the subject's free-driving speed, as determined over the last 30 s before the lead cars started moving. After they had reached their target speed the lead cars moved from the hard shoulder into the driving lanes, and when there was the single leading car it stayed on the right lane. When there were two leading cars these would move into the left and right lane, respectively. When there was the free-driving scenario a single lead car would appear, giving the possibility to overtake. If the subject did not overtake but preferred to stay in a car-following situation, the lead car would get off the road again before the actual start of the scenario. If the subject was to enter the scenario in a car-following situation, two lead cars which could not be overtaken appeared. After a car-following situation had been established, the lead cars would slowly accelerate to the previous free-driving speed again. If the lead cars obeyed the 80 or 100 km/h speed limit, they would decelerate with 1.5 m/s^2 after passing the first beacon setting this speed limit. In the disobedient condition they maintained a constant speed. In the traffic queue scenario the lead cars always braked with a deceleration of 3.5 m/s^2, which exceeds the maximum deceleration of the ICC. After the scenario was finished, the two lead cars always moved back to the hard shoulder, allowing the subject to pass, and to start free driving again.

A VMS was present at intervals of once every 500 m on the entire route. These VMSs could display a maximum speed sign above each individual lane and one other traffic sign in between. The roadside beacon sending a new message to the vehicle was always placed at 50 m before the corresponding VMS, resulting in in-vehicle information or intervention just before passing under the VMS. During a particular scenario, the maximum speed was repeated on each subsequent VMS. The first VMS after the end of the scenario showed the 'end of all restrictions'-sign, and at the same position there also was a beacon sending the corresponding message to the vehicle when it passed there.

The curve appearing in the 'sharp curve' scenario was designed in such a manner that it was rather difficult to negotiate at speeds over 80 km/h. It was a right-hand curve with a radius of 300 m extending over 90°; the speed limit of 80 km/h started at 300 m before the entrance of the curve, enabling a comfortable deceleration to the speed limit.

In the '100 km/h' scenario a 100 km/h speed limit was imposed over a 3 km distance.

In the 'traffic queue' scenario, a queue of ten vehicles (five in each lane) was standing stationary on the road. The end of the queue was at a distance of 300 m after the first VMS that gave a 50 km/h speed limit in combination with a queue warning. After the subject had lowered his speed below 15 km/h the queue would accelerate to 50 km/h, and after a while move to the hard shoulder. The second VMS after that point would indicate the end of the speed limit, which ended the queue scenario.

After having completed the last run subjects who had driven with a candidate ICC filled out a questionnaire asking about their subjective impressions of the ICC. The questionnaire, which was developed in earlier research on candidate collision avoidance systems (Janssen, Brookhuis & Kuiken, 1993) comprised nine specific questions, each allowing a rating on a five-point scale as an answer: see Appendix C. Apart from this, subjects were asked whether they had any general comments to make. These were recorded in writing by the experimenter.

2.5 Data collection and analysis

During the experimental runs the following variables were measured to index subject's behaviour:

- longitudinal position of the subject's vehicle (m)
- speed (m/s),
- longitudinal position of the lead car(s), when these were present (m),
- speed of the lead car(s) when present (m/s),
- status of the ICC system (on/off, overruled, driver's set speed).

From these, several relevant variables were calculated, notably:

- Following distance (m), defined as the distance between the front bumper of the following vehicle (mock-up) to the rear bumper of the simulated lead vehicle travelling in the same lane.
- Headway (s), defined as the time needed for the front bumper of the following vehicle (mock-up) to reach the current position of the rear bumper of the simulated lead vehicle if the following vehicle continues at its present speed. It is calculated as following distance divided by the speed of the following vehicle. From this a criterion was derived to distinguish free-driving from car-following situations. This criterion was set at a 5 s time headway.
- Time-To-Collision TTC (s), defined as the time required for the following vehicle (mock-up) and the simulated lead vehicle to collide if they were both to continue at their present speed. It is calculated as following distance divided by the relative speed (only defined when the speed of the lead car was lower than the follower's speed).

The following variables were, in turn, derived from these to be analyzed:

- *ICC usage*: ICC state, ICC deactivation rate, occurrence of alarm;
- *free-driving speed*: mean and standard deviation (sd), and percentage of time exceeding the posted speed limit;
- *car-following behaviour*: percentage of time spent in a car-following situation, percentage of following during which the time headway was less than 1 s, and mean time headway;
- the mean own speed as a function of the behaviour of the lead car (obedient vs. disobedient);
- *approaching queues*: the TTC and the following distance at the moment the gas pedal is fully released (TTC_{gas} and $Dist_{gas}$, respectively), TTC and following distance at the moment the driver starts pressing the brake pedal (TTC_{br} and $Dist_{br}$ respectively), and the minimum TTC value as reached over the entire manoeuvre (TTC_{min}).

These variables were determined for each scenario separately, where the position just under the VMS indicating a new maximum speed was taken as the beginning of the corresponding scenario.

The questionnaire results were analyzed in two ways. First, in the 'raw' analysis, ratings (with values between 1 and 5) were simply averaged per scale per group of subjects that had worked with a given ICC. The averages were then transformed into a summary score according to the assignment rule given in Table II.

Table II Transformation from Average Score to Summary Score.

Average Score	Summary Score	
1.00 - 1.50	+ +	+2.00/+1.51
1.51 - 2.50	+	0.51/1.50
2.51 - 3.49	o	-0.50/+0.50
3.50 - 4.49	-	-0.51/-1.50
4.50 - 5.00	- -	-1.51/-2.00

Second, the questionnaire ratings were subjected to a dimensional analysis on the basis of the earlier findings from Janssen, Brookhuis and Kuiken (1993). These authors showed that two factors ('Perceived Usefulness' and 'Perceived Comfort') were sufficient to cover the original nine rating scales. The known loadings of the original items on these factors were applied to the current 'raw' ratings given by subjects in order to obtain composite scores for each factor for each ICC.

The results were tested for statistical significance by means of analyses of variance (ANOVA). No complete factorial experimental design was used, and therefore it was not possible to compare all ten groups in one ANOVA. The approach followed was first to test if an effect of 'block' occurred in the control group. Since in this group both blocks were carried out without ICC, an effect of 'block' could be caused by factors like fatigue and learning effects. For groups 2 to 10, on the other hand, the block number indicated the absence/presence of an ICC. Therefore, if no effect of 'block' is found in the control group, then the occurrence of such an effect in the other groups could be attributed to the ICC.
Next, the two groups without communication (i.e., the control group and the group with independent ICC) were compared. If there is an effect of the independent ICC, this would give an interaction between 'group' and 'block'. Finally, the remaining eight groups are compared in one ANOVA, using ICC mode (informative/ intervening), feedback type (basic/visual/acoustic/haptic), and block number (1/2) as factors.
Since no a priori hypotheses had been formulated about differences between various systems, post hoc tests were used to test the significance of specific differences found between means (Newman-Keuls), also using a significance level of $\alpha = 0.05$.

3 RESULTS

3.1 **Overall ICC usage**

To start with, some general results concerning ICC usage will be discussed, showing how long the ICC was 'on' or 'off' in different situations, or how often switching occurs. The reason to investigate this is the possibility that certain systems are switched of more often than others, for instance because subjects find them irritating or annoying. These results were determined over all ICC runs, i.e. the second block of groups 2 to 10.

State of the ICC

Averaged over all ICC runs, the ICC was 'off' in 22.4%, 'on but overruled' in 6.3%, and 'on and not overruled' in 71.3% of the time. These percentages are depicted as a function of scenarios in Fig. 2. ANOVAs showed that these percentages all differed significantly across the different scenarios [all $p < 0.001$].

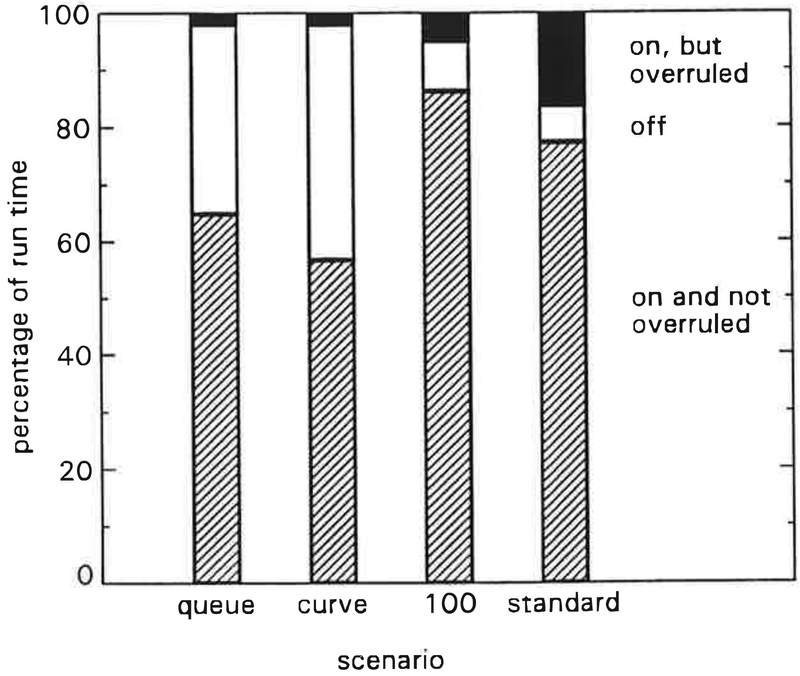

Fig. 2 Percentages of usage of each ICC state as a function of scenario.

Subjects did follow the instruction of 'keeping the ICC on as much as possible': in the '100 km/h' and 'standard' scenarios it was on during 92% of the time. In the queue and curve scenario this was less, namely 62%. Overruling of an ICC occurred mainly on the 'standard' sections (16%). An ANOVA on the percentages the ICC was 'off', using the factors feedback type and ICC mode, showed only an effect of scenarios [$F(3,120) > 48$, $p < 0.001$], but not of ICC mode or feedback type [$p > 0.57$ and $p > 0.16$, respectively]. Also for the percentage the

ICC was 'on but overruled' there was only an effect of scenario [$F(3,120) > 18.6$, $p < 0.001$], and again, no effects of ICC mode or feedback type were found [$p > 0.9$ and $p > 0.8$, respectively]. Apparently, the differences in system configuration do not lead to different ICC usage.

Deactivation of the ICC

As described in section 2.2, the ICC could be switched off manually by means of a switch on the steering wheel column, but it also switched off as soon as the subject released the gas pedal. Averaged over all ICC runs, the ICC was switched off with a frequency of 0.4 times per minute (i.e. once every 2.6 minutes). This was usually done by releasing the gas pedal. Only 8.2% of all ICC deactivations were carried out using the switch. It should be noted, however, that a release of the gas pedal does not necessarily indicate an intentional deactivation.

To investigate the situations in which the subjects typically deactivated the ICC three categories were distinguished:
- the ICC is switched off when a new, more restrictive speed limit applies;
- the ICC is switched off when a lead car is present in the same lane; and
- the ICC is switched off after it has been on for less than 1 s (this happens when the subject tries to engage the ICC without his foot on the gas pedal).

These categories are not mutually exclusive. For instance, the ICC could be switched off in a situation where a new speed limit applies *and* a lead car is present. Therefore, for each single deactivation it was determined which categories applied. If more of them applied simultaneously, the counters of the corresponding classes were increased by the reciprocal of the number of categories that applied (i.e., 1/2 each if two categories applied, and 1/3 each if all three categories applied).

Separate ANOVAs on these percentages revealed no effects of feedback type or ICC mode; there was only an effect of scenario [all $p < 0.02$]. The results are shown in Fig. 3. It appears that the total frequency of deactivation is the highest in the two most urgent scenarios (i.e. the 'queue' and the 'curve' scenario). Disengaging the ICC near a new speed limit occurred only on the 120 km/h stretches, i.e. before passing the maximum speed sign that was going to apply on the next road section. The number of deactivations in the presence of a lead car was highest in the queue scenario. This was to be expected because in that scenario lead cars were always present, whereas the remaining scenarios always included some period without the presence of other traffic. The frequency of disengaging the ICC after being on for less than 1 s shows the same pattern over the various scenarios as the total number of deactivations. These deactivations (or, in fact, unsuccessful activations) occur relatively quite often. Apparently the subjects had some problems with keeping their foot on the gas pedal when engaging the ICC. Again, the differences in system configuration do not result in different ICC usage.

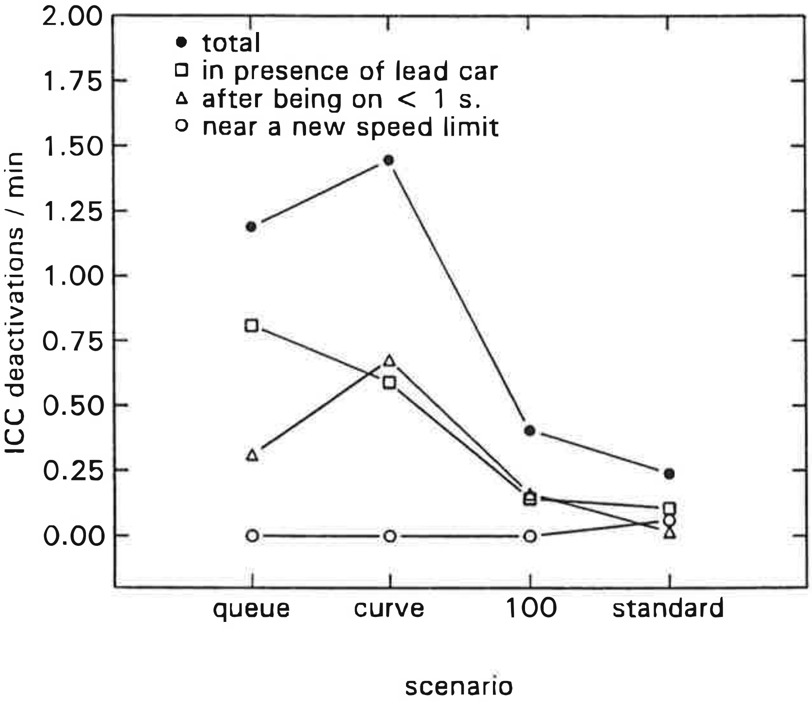

Fig. 3 Number of ICC deactivations per minute for each scenario.

Occurrence of alarm for approaching too fast

When the ICC was on and the subject was closing in on a lead car so fast that the ICC could not cope with it, an alarm was sounded. Not surprisingly, this happened in the 'queue' scenario only, with an average of 0.56 times per run. No difference in the number of times the alarm was triggered was found among the various feedback types and ICC modes.

3.2 Free-driving speed

The analysis of free-driving speeds was carried out on all free-driving sections of the runs, i.e. where the time headway was longer than 5 s. The first 120 s of each run were discarded, since this included the acceleration from standstill to the desired free-driving speed. Similarly, the first 300 m after the introduction of a new speed limit were not included in the analysis.

Mean free-driving speed

The ANOVA on the mean free-driving speed of group 1, with block number and scenarios as factors, revealed no effect of block number [$F(1,5)=1.0$, $p>0.35$]. This analysis indicates that there are no order effects caused by non-experimental factors like fatigue or getting used to the scenarios. There was only

an effect of scenario [$F(3,15)=208$, $p<0.001$]: as was to be expected, the mean speed increased with increasing posted speed limits.
The ANOVA for the ICC conditions 1 and 2 (i.e., the control group compared to the group driving with an independent ICC), with the factors block number, group number, and scenario showed the same main effect of scenario [$F(3,30)=383$, $p<0.001$] (Fig. ???4a). There was a trend showing that the mean speed was higher in the control group than in the independent ICC group [$F(1,10)=3.1$, $p<0.1$], but this was the case in both blocks, indicating that there was a structural difference between the two groups. More importantly, there was no effect of block number [$p>0.5$] and no interaction between block and group [$p>0.5$], which means that the presence of the independent ICC does not influence the mean speed. Therefore, any effect to be found in the remaining ICC conditions (groups 3-10) are caused by the combination of ICC with the communication system.

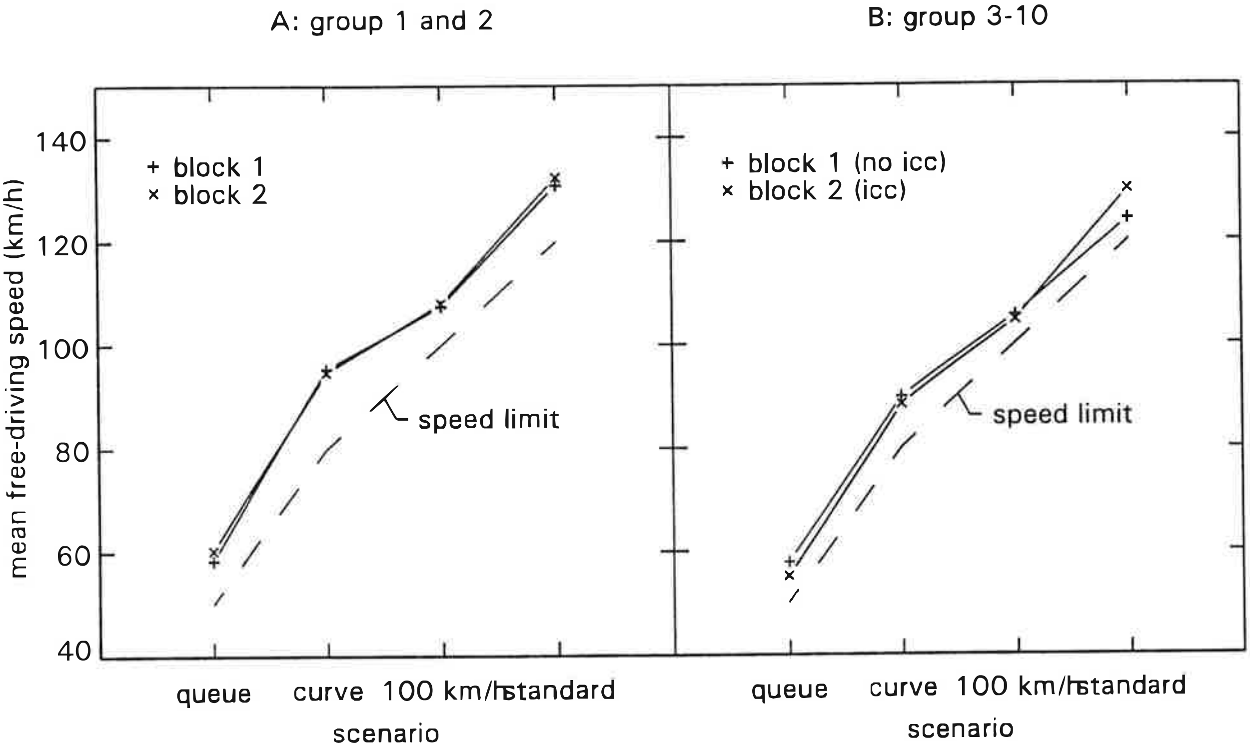

Fig. 4 Mean free-driving speed as a function of scenario and of block number. **A**: control group and independent ICC; **B**: ICCs with communication.

The ANOVA on the mean free-driving speed with scenarios, feedback type and ICC mode as independent variables also showed an effect of scenarios [$F(3,120)=1215$, $p<0.001$]; see Fig. 4b. There was also a significant interaction between block number and scenarios [$F(3,120)=16.1$, $p<0.001$]. A Newman-Keuls post hoc test showed that the presence of ICC (in block 2) lowered the

mean free-driving speed in the 'queue' scenario [$p < 0.01$], but also that it raised the speed on the 120 km/h sections [$p < 0.001$].
A significant third order interaction existed between ICC mode, block number (i.e. with vs. without ICC), and scenarios [$F(3,120) = 4.0$, $p < 0.01$]; see Fig. 5b. In the informative condition, the Newman-Keuls test revealed no effect of block number on the mean free-driving speed in any of the three critical scenarios [all $p > 0.74$], and a slight speed increase on the 'standard' sections [$p < 0.01$]. In the intervening condition, on the other hand, the Newman-Keuls test showed that free-driving speeds were lowered by ICC presence in the queue and curve scenarios [$p < 0.001$ and $p < 0.05$, respectively], but on the 'standard' sections the speed was raised when introducing ICC [$p < 0.001$]. This speed increase caused by the ICC presence was higher in the intervening condition than in the informative condition [$p < 0.001$].

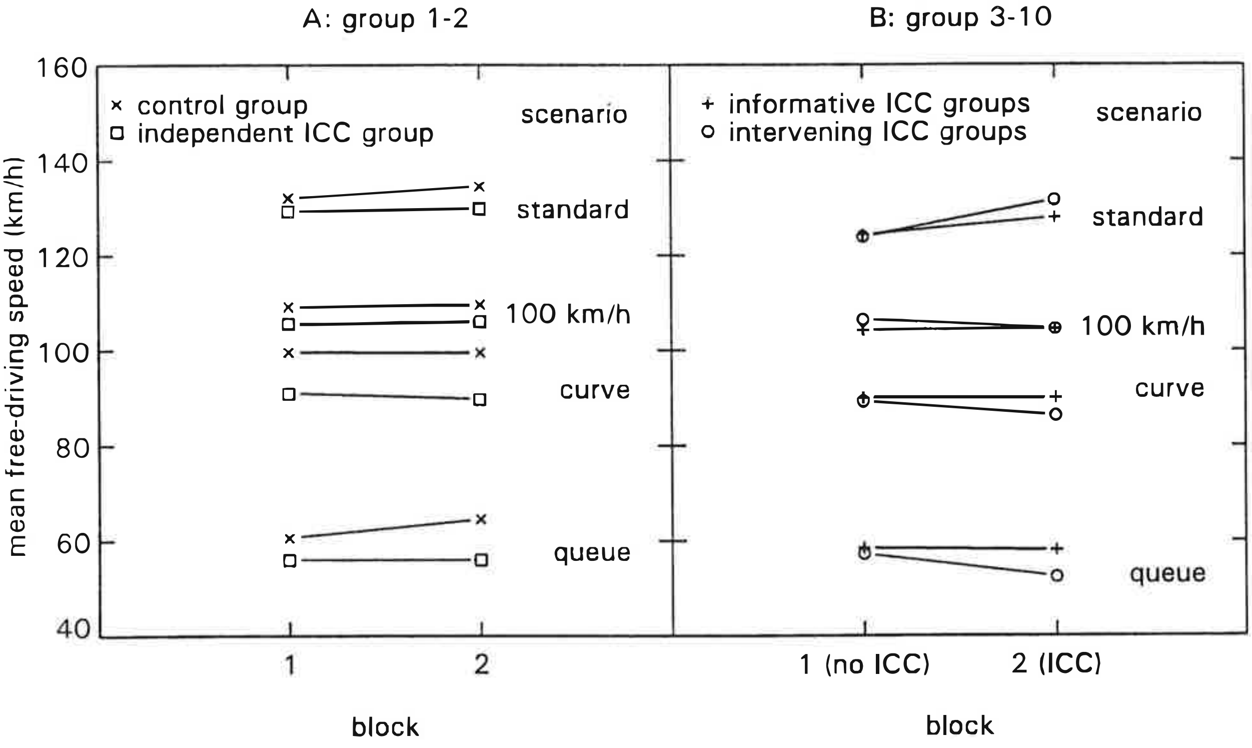

Fig. 5 Mean free-driving speed as a function of scenario, block, and ICC mode. **A**: control group and independent ICC; **B**: ICCs with communication.

Standard deviation of free-driving speed

The standard deviation (sd) of the free-driving speed was determined over the same time periods as the mean free-driving speed. The ANOVA on the control group, with scenarios and block number as factors, only revealed an effect of scenarios [$F(3,15) = 13.2$, $p < 0.001$]; there was no effect of block number [$p > 0.9$], i.e. no order effects were found.

Also the ANOVA with groups 1 and 2, using group number, block number and scenarios as factors, revealed that the sd differed only over the scenarios [$F(3,30)=28.4$, $p<0.001$]. Group or block number were not significant factors [both $p>0.38$].
The ANOVA with the factors ICC mode, feedback type, block number, and scenarios, showed the same effect of scenario [$F(3,120)=72.2$, $p<0.001$]. Also a main effect of block number was found: in block 1 the sd is 6.7 and in block 2 it is 5.9, so the sd is lowered by the presence of ICC [$F(1,40)=5.2$, $p<0.05$]. Furthermore, there was a significant interaction between ICC mode and block number [$F(1,40)=6.3$, $p<0.02$]; a Newman-Keuls test showed that this was caused by a decrease of the sd in the intervening condition (from 6.9 in block 1 to 5.1 km/h in block 2) [$F<0.01$], whereas in the informative condition no effect was found [$F>0.8$]. Apparently, the main effect of block number can only be attributed to the intervening ICCs. Furthermore, a third-order interaction was found between ICC mode, block number, and scenarios [$F(3,120)=2.8$, $p<0.05$]. The Newman-Keuls tests showed that this interaction could be attributed to a decrease of the sd in the queue scenario [$p<0.002$] and in the standard scenario [$p<0.02$]. In none of the remaining scenarios or conditions an effect was found. In conclusion, a decreases of the (within-subjects) sd of the free-driving speed was only found in two scenarios in the intervening ICC mode.

Exceeding the posted speed limit

The percentage of the time the actual free-driving speed exceeded the posted speed limit was analyzed for all experimental conditions. The ANOVA on this percentage for group 1 only, with block number and scenarios as factors, revealed no effect of block number [$p>0.6$], i.e. no order effects were found.
The ANOVA for groups 1 and 2 (control vs. independent ICC), with block number, group number, and scenarios as factors, showed a main effect of scenarios only [$F(3,30)=5.5$, $p<0.005$], see Fig. 6a. The overall mean was 89%; the smallest and largest percentages were 76% and 96% in the queue scenario and in the 100 km/h scenario, respectively. There were no effects of group or block number [both $p>0.5$], and an interaction between these factors was not present either [$p>0.6$]. Therefore, if effects or interactions are found in the remaining ICC conditions, these can only be attributed to the combination of ICC with a communication system.

The ANOVA on the percentage of time in exceedance of the speed limit, with scenarios, block number, ICC mode, and feedback type as factors, also revealed an effect of scenarios [$F(3,120)=7.9$, $p<0.001$]. In this analysis, moreover, there were significant interactions between ICC mode and block number [$F(1,40)=6.1$, $p<0.02$], between block number and scenarios [$F(3,120)=17.3$, $p<0.001$], and between ICC mode, block number and scenarios [$F(3,120)=3.3$, $p<0.05$]. These results are summarized in Fig. 6b. The Newman-Keuls test showed that for subjects with an informative ICC, the ICC presence had no effect on the percentage of time the speed limit was exceeded in any of the critical scenarios [all $p > 0.63$]; on the standard sections, the ICC presence resulted in a higher percentage [$p < 0.01$]. For subjects with an intervening ICC, the ICC lowered percentages in the 'queue' and in the '100 km/h' scenarios [$p < 0.005$ and $p < 0.001$, respectively]. On the standard sections the percentage was found to increase [$p < 0.02$].

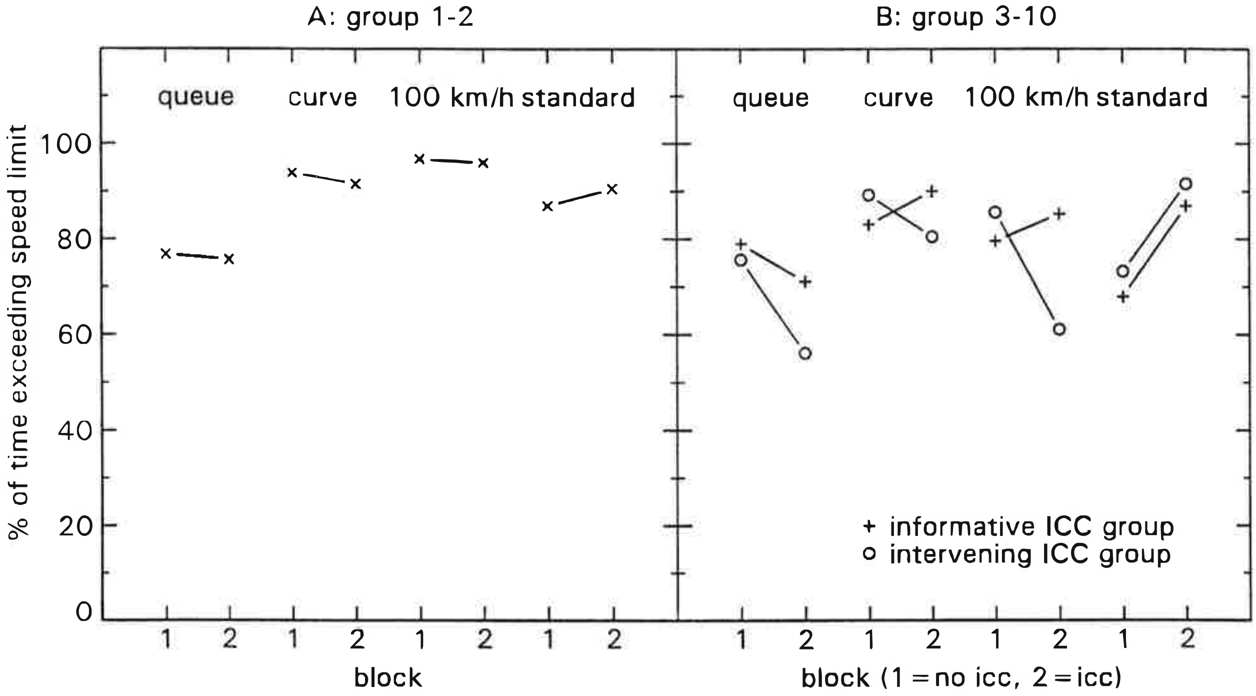

Fig. 6 Percentage of time exceeding the posted speed limit as a function of scenario, block number, and type of ICC mode. **A**: control group and independent ICC; **B**: ICCs with communication.

3.3 Car-following behaviour

Two parameters describing car-following have been analyzed: the percentage of time subjects were in a car-following situation (as defined by a time headway of less than 5 s), and the percentage of following during which the time headway was less than 1 s.

The ANOVA for group 1 on the percentage of time subjects were in a car-following situation, with block number and scenarios as factors, revealed no effect of block number [$p > 0.6$]. The ANOVA on groups 1 and 2, with group number, block number, and scenarios as factors, showed no difference in this percentage either. Finally, in the ANOVA with block number, scenarios, ICC mode and feedback type as factors, no such effect was present either. The percentage did, however, vary over the different scenarios in all three ANOVAs [all $p < 0.001$], which was probably due to the specific nature of these scenarios.

For example, since there were always leading vehicles in the 'queue' scenario the percentage of car-following in that scenario would naturally be expected to be higher than in the other scenarios. In conclusion, the percentage of time subjects were in a car-following situation was not influenced by any of the ICCs.

The percentage of following during which the time headway was less than 1 s was also analyzed. An ANOVA on this percentage for group 1 only, with block number and scenarios as independent variables, showed no effect of block number [p > 0.18].

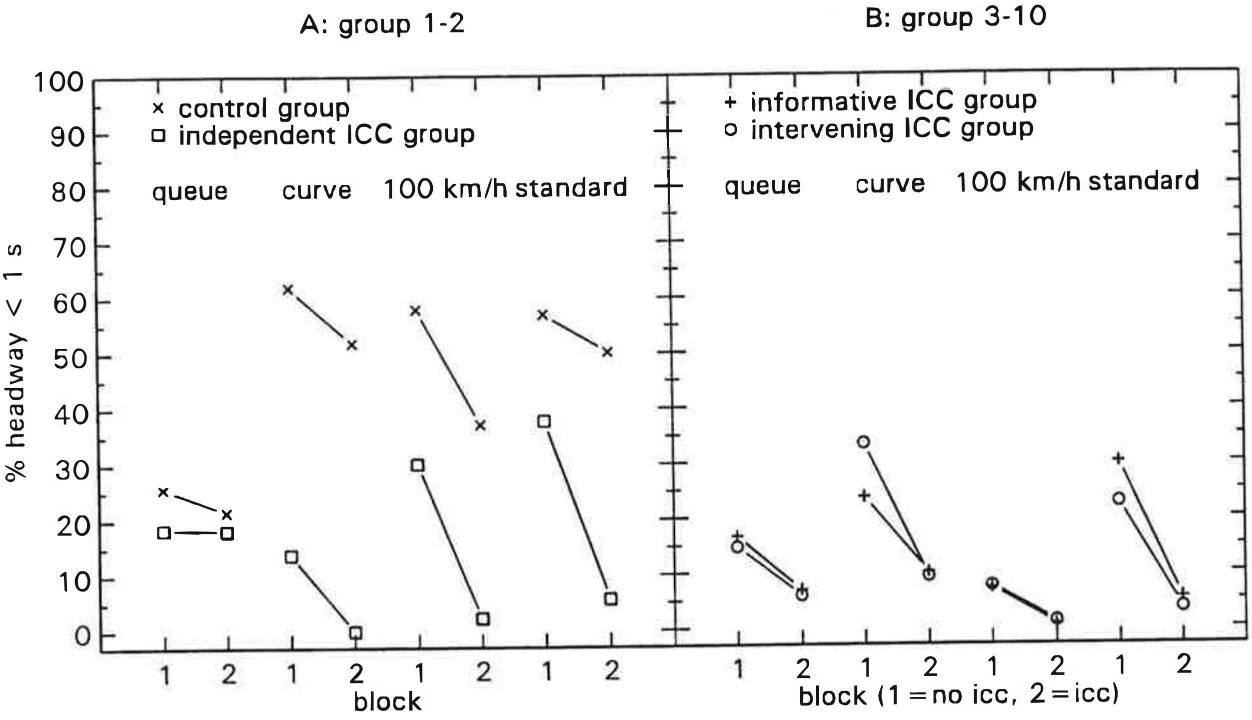

Fig. 7 The percentage of time headway < 1 s (over all following situations) as a function of scenario and of block number. **A**: control group and independent ICC; **B**: ICCs with communication.

The ANOVA on groups 1 and 2, with group number, block number and scenarios as factors, however, did show an effect of block number [$F(1,6) = 9.5$, $p < 0.05$]: in the second block the percentages were smaller, see Fig. 7a. There was no significant difference between the control group and the group with independent ICC [$p > 0.12$]. There was no interaction between group number and block number [$p > 0.4$]. Based on this, one would have to conclude that for the control group, the percentage of small headways was smaller in the second block than in the first block, which is contradicting the results of the first ANOVA. Apparently, a factor like getting used to the scenarios may have played some role here in the control group.

The ANOVA with feedback method, ICC mode (informative vs. intervening), block number (i.e. ICC presence) and scenarios as factors showed significant effects of block number and of scenarios [$F(1,21)=24$, $p<0.001$, and $F(3,63)=4.4$, $p<0.01$, respectively]. As Fig. 7b shows, the percentage of short headways is smaller in the presence of ICC.

ANOVAs on the mean time headway (for the distribution of all headways below 5 s) showed no effects of block number or system configuration.

3.4 Own speed as a function of the behaviour of leading vehicles

The mean speed in the curve and the 100 km/h scenarios in the presence of lead cars was determined separately for the cases where the lead car did and where it did not obey the posted speed limit.

An ANOVA with group 1 only, with obedience, block number and scenarios as factors, revealed only a significant main effect of scenario [$F(1,4)=19$, $p<0.02$].
The ANOVA with group 1 and 2, with obedience, block number, group number, and scenarios as independent variables, showed main effects of obedience [$F(1,8)=14.6$, $p<0.01$] and of scenarios [$F(1,8)=80.3$, $p<0.001$]: as was to be expected, speeds were higher when the lead cars did not comply with the speed limit and when the speed limit itself was higher. There were no significant differences between means in the first and the second block [$p>0.5$].
The ANOVA with feedback type, ICC mode, obedience and scenarios as factors showed similar effects of obedience and of scenarios [$F(1,32)=36.9$, $p<0.001$, and $F(1,32)=137$, $p<0.001$, respectively]. There was also a significant interaction between obedience and block number [$F(1,32)=4.3$, $p<0.05$]; this is shown in Fig. 8 for the two scenarios separately. A Newman-Keuls test showed that the decrease of the mean in the disobedient condition, when an ICC is available, was marginally significant [$p<0.07$]. In the 'obeying' condition, the mean in the curve scenario was not significantly higher with ICC than without ICC. The fact that in that condition the mean speed (82.5 km/h) exceeded the lead car's speed of 80 km/h was caused by the behaviour of some subjects in the section prior to the curve. These subjects initially reduced their speed, thus creating a large following distance, and once in the curve this allowed them to exceed 80 km/h without conflicting with the lead cars.

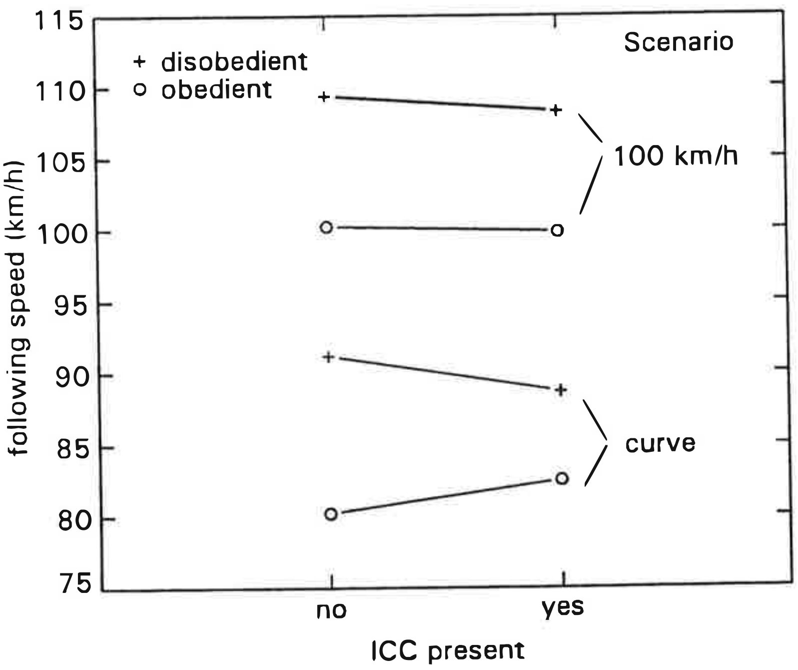

Fig. 8 Mean speed in 'curve' and '100 km/h' scenarios with lead cars as a function of block number and lead car obedience (groups 3-10).

3.5 Approaching queues

Those episodes in which the subject approached the stationary traffic queue without the presence of leading cars were analyzed separately.

The ANOVAs for group 1 only, with block number as the only independent variable, did not reveal an effect on any of the dependent variables listed in Table III [all $p > 0.35$]. Likewise, the ANOVAs for groups 1 and 2, with group number and block number as factors, did not show any effect or interaction either [all $p > 0.25$].

Table III Results of ANOVAs on approach variables (group 3-10).

Variable	Mean, no ICC (block 1)	Mean with ICC (block 2)	F(1,40)	p
TTC_{gas}	11.1 s	9.5 s	10.5	0.005
TTC_{br}	9.3 s	7.9 s	8.0	0.01
TTC_{min}	4.6 s	3.9 s	4.9	0.05
$Dist_{gas}$	368 m	321 m	6.2	0.02
$Dist_{br}$	299 m	265 m	3.7	0.07

The ANOVAs with ICC mode, feedback type, and block number as factors revealed effects of block number (i.e. ICC presence) on TTC_{gas}, TTC_{br}, and TTC_{min}: these variables were all smaller when ICC was present. The averages are listed in Table II.

Since the free-driving speed on the section prior to the queue scenario was overall highest in the ICC conditions (as discussed in Section 3.2), a decrease in TTC measures would be obtained if the subjects reacted at a constant distance to the queue. An ANOVA on $Dist_{gas}$ and $Dist_{br}$ (the distance to the queue at the moment the gas is released and the moment the brake is pressed, respectively) was carried out to investigate this possibility. $Dist_{gas}$ was significantly smaller when ICC was present, and $Dist_{br}$ showed a nearly significant decrease. Hence, the smaller TTC values can be attributed both to the higher approach speeds *and* to the smaller distance to the queue at which the deceleration is initiated.

The mean deceleration level a_{mean}, determined over the entire braking period, was also analyzed. The ANOVA for group 1 only, with block number as the independent variable, revealed no effect [$p > 0.15$]. The ANOVA for group 1 and 2, with block number and group number as factors, revealed a significant interaction between group number and block number [$F(1,10) = 7.9$, $p < 0.02$]. The Newman-Keuls test showed that this was caused by an almost significant increase of a_{mean} in group 2 [$p < 0.1$]; in group 1 no significant change was found [$p > 0.27$], in correspondence with the results of the ANOVA on group 1 only.
An increase of the a_{mean} was also found in the ANOVA with ICC mode, feedback type, and block number as factors: the means were 2.9 m/s^2 without, and 3.3 m/s^2 with ICC [$F(1,40) = 5.8$, $p < 0.05$]. The fact that the braking was initiated later results in larger decelerations needed to stop before colliding with the queue.
The maximum deceleration reached over the entire approach phase was not significantly influenced by block number or ICC configuration; its mean value was 6.1 m/s^2.

3.6 Questionnaire results and general comments made by subjects

Questionnaire results were analyzed both in a raw and a factor-analytic form. The raw analysis yielded the results of Table IV. Here the ratings given by subjects on the original 9 scales of the questionnaire have been averaged, and assigned summary scores per scale, as described in Section 2.5.

Table IV Summary scores per original scale per ICC.

ICC MODE	(indep)	informative				intervening			
FEEDBACK	(none)	basic	visual	acous	hapt.	basic	visual	acous	hapt.
GROUP NR	2	3	4	5	6	7	8	9	10
useful	+	+	+	+	+	+	+	+	+
pleasant	+	+	+	+	+	+	+	o	+
good	+ +	+	+	+	o	+	+	-	+
effective	+	+	+	+	o	+	+	+	+
nice	+	+	+	+	o	+	o	-	+
desirable	+	o	+	+	+	+	+	o	+
congenial	+	+ +	+	+	o	+	+	o	o
helpful	+	+ +	+	+	+	+	+	+	+
alerting	o	o	o	o	+	-	+	o	o

The results as given in Table IV show that ICCs differed in the judgments they evoked in the subjects. Overall, the intervening ICC that made use of acoustic feedback was judged the most unfavourable. Of the remaining systems not a single one received favourable ratings on all scales. Systems 2, 4, 5 and 8 were judged to be positive on 8 out of 9 scales, and neutral on the remaining one.
Remarkably enough, most non-favourable judgments were on the 'alertness' scale, obviously reflecting a belief that ICC-systems may possess an inherent danger of lulling drivers asleep.

The factor-analytic results are expressed as averaged composite scores on the dimensions of 'Perceived Usefulness' and 'Perceived Comfort', which are relative measures. They are shown in Fig. 9.
Fig. 9 shows that most ICCs (7 out of 9) were considered relatively useful, and that 4 out of this group of 7 were also considered relatively comfortable. One ICC, the intervening one with the acoustic feedback, was judged to be both extremely useless and uncomfortable. Inspection of the raw results showed that this was due to the ratings given by two subjects, who apparently showed an extreme dislike for this particular ICC.

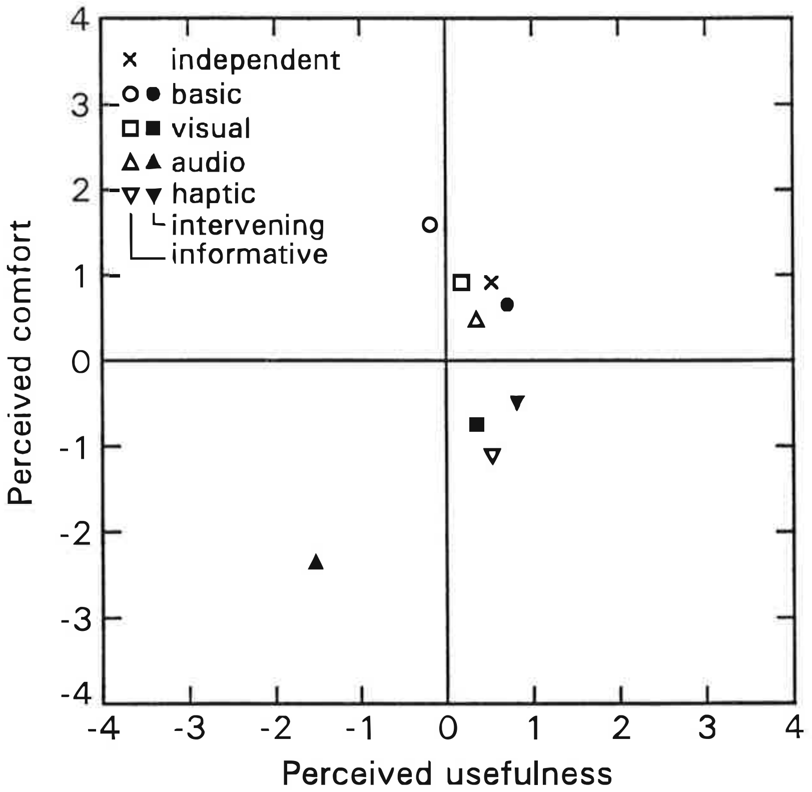

Fig. 9 Scores on 'Perceived Usefulness' and 'Perceived Comfort' of candidate ICCs.

The conclusion to be drawn from the subjective rating results is that there are apparently ICCs which are judged favourably on both perceived usefulness and perceived comfort, but that there is no single way in which these judgments are related to the ICC's underlying design dimensions.

The general comments made by the subjects do not lend themselves to substantial forms of quantitative analysis, certainly not when it comes to more subtle differences in design between different ICCs. Two comments on overall ICC functionality were given by more than 10% of the 54 subjects in the ICC condition. These were:

- 'Foot should not have been kept on gas pedal in order to keep system on' (15 subjects, or 28% of total)
- 'Too many controls, warning lights, etc., divert attention' (11 subjects, or 20% of total).

4 DISCUSSION AND CONCLUSIONS

This experiment compared the behaviour of drivers working with several forms of cruise control in different relevant scenarios. The behavioral measurements taken were related to the two aspects that modern cruise controls are directed to, viz. the regulation of one's own speed and that of car-following performance. The ICCs studied varied in the way in which relevant information was presented to drivers and the way in which control was exerted by the ICC. The final part of this report discusses the findings that were obtained as they relate driver behaviour to the variations in ICC design.

The general expectations of ICC (regardless of the presence of in-vehicle information) are that, compared with a human driver, speed and following distance are controlled with less variation. The standard deviation of the free-driving speed was seen to decrease in some ICC conditions. With respect to car-following it was found that the percentage of short time headways (< 1 s) was lowered by introducing ICC, as could be expected by a system that aims at maintaining a headway of 1.5 s. The mean headway was not significantly affected by the existence of an ICC, and therefore the reduced percentage of short headways was not obtained at the cost of an overall increase of headways.

However, the main subject of this study was not ICC as such, but ICC combined with a communication system that provides in-vehicle information. Since the in-vehicle information consisted of speed related messages, the primary question is whether specific ICC configurations result in changes in driving speed compared to the conditions without ICC. It was found that in the critical scenarios a reduction of the mean free-driving speed was only obtained when the posted speed limit was automatically put into the ICC. However, even in this intervening condition, the mean speed still exceeded the speed limit simply because some subjects overruled or disengaged the ICC. The other forms of ICC (informative or no communication) did not result in an extra speed reduction in the critical scenarios compared to the runs without ICC.
On the standard road sections, where no beacons were present, the mean free-driving speeds *increased* after introducing the intervening ICC/communication system. There seems to be a compensating mechanism in that actively reducing a driver's speed on a few limited sections makes him drive faster on other parts. However, also when the communication system just presented information during the scenarios a speed increase was found on the normal sections. Given the relation between speed and traffic safety (Nilsson, 1984), this can be considered as an unwanted effect. A straightforward measure to prevent this compensatory effect seems to be to use beacons on the 'standard' sections as well, that is to give information and/or intervene when the speed limit is 120 km/h. It should be noted, however, that the subjects were instructed to use the ICC as much as possible. When the driver has the liberty to disengage or overrule the system, the effectivity of any intervening system might be reduced correspondingly.

ICCs are generally designed for a limited range of accelerations and decelerations. This implies that in emergency-like situations requiring larger decelerations than the ICC's limit, the driver must take over control. There are several reasons why a driver, in such a situation, could react later compared with the condition without ICC. First, since ICC adequately takes care of the longitudinal control most of the time, it could cause a decreased alertness of the driver. Second, even if the driver is aware of the dangerous situation, he could have too much confidence in the ICC's capabilities to deal with it. Third, the presentation of in-vehicle information at the same time that a critical situation is developing could distract the driver's attention from the traffic, especially when a visual display is used. Important questions are whether drivers are capable of judging correctly what the ICC's limits are, and when and how the driver should be warned if the ICC cannot cope with the situation. In the current experiment an acoustic warning signal was given when the ICC's maximum deceleration was insufficient to avoid a collision with the lead car, but that is not necessarily the optimal approach.

In this experiment, the most critical scenario was the approach to a stationary traffic queue. This scenario is similar to that of an earlier field experiment by Van der Horst (1990), in which subjects approached a simulated rear-end of a car with the instruction to start braking at the latest moment they thought they could stop just in front of the object. The results showed that both the decision to start braking and the control of braking may well be based on TTC information as directly available to the driver from the optic flow field. When subjects are asked to apply a minimum margin (Van der Horst, 1990), a more or less constant TTC_{min} of 1.1 s results. In the current experiment, during the approaches to the stationary traffic queue which were without a lead vehicle, subjects started braking when TTC was about 8 s in the case when there was no ICC-support. When there was support of an ICC/communication system, the mean approach speed was higher, and the braking started at a smaller distance to the queue, resulting in smaller TTC_{br} values. Furthermore, the mean TTC_{min} was lowered from 4.6 to 3.9 s after adding ICC, but this is still well above the 1.1 s reported by Van der Horst (1990). Therefore, the driver's reaction does start somewhat later, but this is only a moderate shift towards a minimum-margin situation.

In this experiment, an effect of feedback type was not found on any of the dependent variables. The basic feedback in the form of a flashing LED combined with a 'beep' gave no different results from more sophisticated systems in which visual displays, spoken messages, or vibrations on the gas pedal were added to the basic configuration. Apparently, the LEDs already comprise an effective feedback method. However, what also may have played a role is that all in-vehicle information was essentially redundant, since the speed limit and its rationale were always visible on the roadside VMS. The motivation for always using roadside information was that when considering implementing these systems in reality, the roadside information would always be required as long as not all vehicles have in-vehicle information. Differences between the various feedback systems may occur when they would be exclusively in-vehicle, that is, when no roadside information would be present. This possibility would have to be investigated in an additional experiment.

With respect to having to keep one's foot on the gas pedal while the ICC was on, a number of disadvantages was found. Many subjects complained about that MMI approach: apparently it strongly reduces the subjective comfort provided by an ICC. The large proportion of unsuccessful ICC activations (i.e. attempts to activate the ICC without a foot on the gas pedal, see Section 3.1) shows that subjects actually have some difficulty using this system. During the implementation of the ICC in the driving simulator it already appeared complicated to combine all required functions in one gas pedal: the driver must keep his foot on the pedal to keep the ICC on, but at the same time he must be able to overrule the ICC temporarily and then let the ICC take over again. The various ICC states ('off', 'on and not overruled', 'on but overruled') had to be clearly distinguishable for the driver, which was difficult to achieve.
The current approach was originally based on two considerations. The first is that it is safer if the driver keeps his foot on the pedal because in a sudden emergency situation his foot is at a well-defined place without the danger that he places his foot on the gas pedal instead of the brake. Secondly, feedback by means of an active gas pedal can only be applied with the foot on the pedal. However, with respect to the safety issue, one may also argue that the brake reaction time can be reduced when the driver does not have to have his foot on the gas pedal because then he can anticipatorily keep his foot near the brake pedal. With the foot on the gas pedal, however, an additional foot movement from the gas to the brake pedal is required after the decision to start braking. With respect to the second argument, since the condition with feedback by means of the active gas pedal did not give different results than the other feedback types, this does not provide the necessity to maintain the current solution. This could change, however, when one considers to combine ICC with a Collision Avoidance System (CAS). Janssen (1993) showed that a CAS based on a TTC criterion, combined with feedback by means of an active gas pedal is the most effective.

With respect to the judgments given by the subjects about the ICC they had been working with, it appeared that they were reasonably satisfied with most systems, with the exception of the intervening system that made use of acoustic feedback. There was quite a general tendency, however, to judge ICCs as potentially diminishing alertness while driving. Comments of that nature were also explicitly made by a number of subjects after the experiment.

In conclusion, we have found evidence that different forms of ICC combined with in-vehicle information show fairly consistent effects on driver behaviour, not all of them being favourable effects. A configuration where a beacon automatically passes speed limits on to the ICC can be effective to reduce speeds in critical scenarios. However, drivers appear to compensate for such automatic speed reductions by driving faster on sections without beacons. At the same time the combination of ICC with a beacon system resulted in somewhat later braking of the drivers in situations the ICC could not cope with. There were little or no effects of the way the ICCs were designed in terms of, for example, informative mode. As discussed above, this could be caused by the redundancy in the information, but also by the basic feedback configuration already being sufficiently clear.

From this study some issues remain to be resolved. Especially, it is recommended to focus on:
- the effects of 'classical control' (foot off gas instead of on gas) on driver acceptance and driver behaviour, especially brake reaction times;
- the effect of removing redundancy in informative and feedback modes. This can clarify whether in-vehicle information is useful at all as long as there is road-side information too;
- the optimal settings of ICC controller parameters, for instance headways smaller than the current 1.5 s in relation to driver acceptance and driver behaviour; and
- the possible decrease of alertness caused by ICC usage, or the possible divergence of attention from the driving task itself to dealing with the ICC controls and displays.

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Soesterberg, 12 July 1994

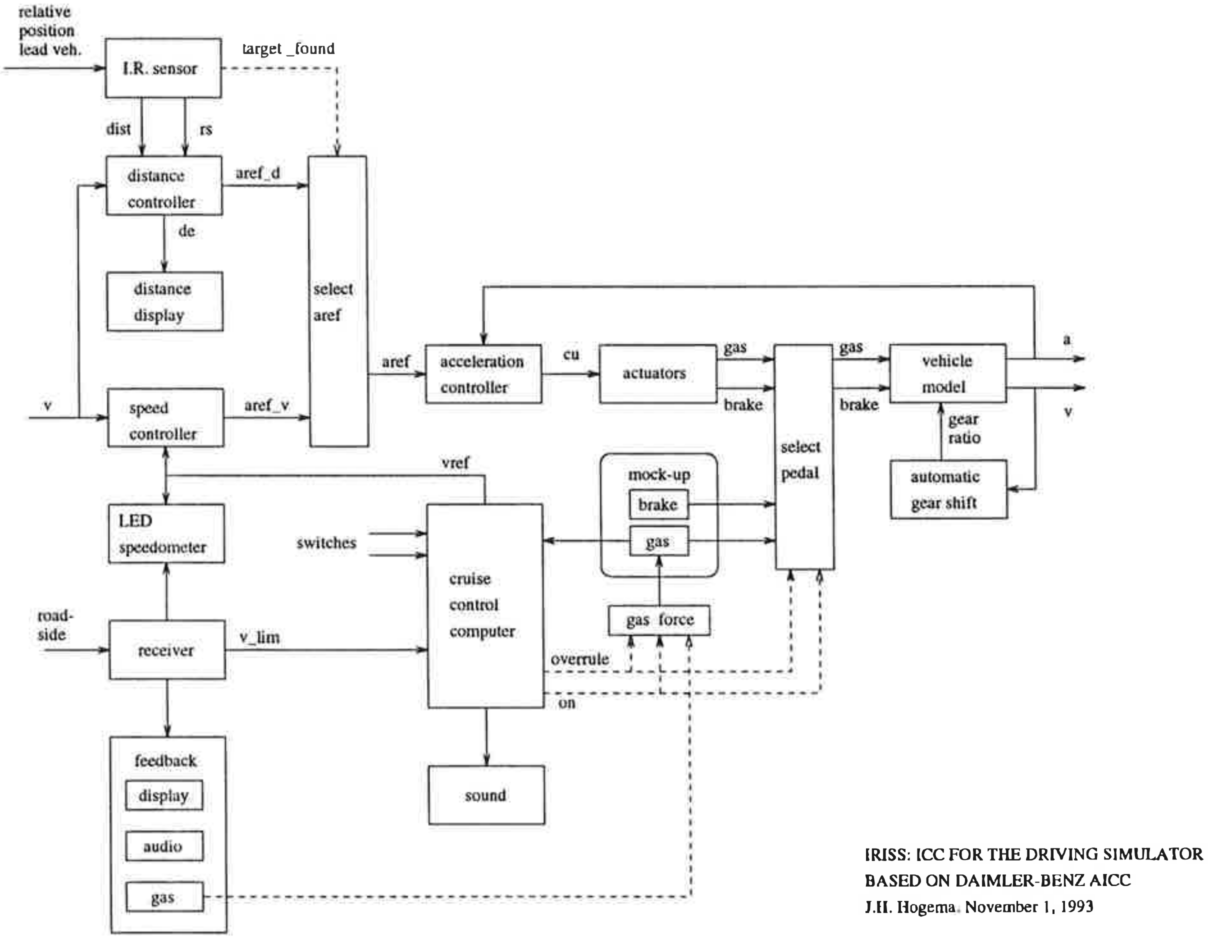
J. Hogema

Ir. J.H. Hogema

APPENDIX A Technical description of the ICC

The logic of the ICC implemented in the TNO driving simulator for the present experiment was based on the Daimler-Benz approach to AICC, as described in Müller and Nöcker (1992). This is a fuzzy based ICC, using an infrared distance sensor and a drive-by-wire actuator system that allows accelerating and braking.

A block diagram of the entire system is given in Fig. A1; its components will be explained below. Text in italic refers to block or signal names in Fig. A1.



IRISS: ICC FOR THE DRIVING SIMULATOR
BASED ON DAIMLER-BENZ AICC
J.H. Hogema. November 1, 1993

Fig. A1 Block diagram of the ICC system.

The *vehicle model* is the same model used in other experiments in the driving simulator. At a frequency of 90 Hz, it calculates among other things the momentaneous position (X-, Y-, and FI-coordinates) of the simulated vehicle, which has the dynamic characteristics of a Volvo 240 (Godthelp, Blaauw & Van der Horst, 1982). The outputs of this model relevant for the ICC are the longitudinal acceleration *a* and speed *v*. Based on the current speed *v*, an *automatic gear shift* function calculates an appropriate gear ratio.

Inputs to the vehicle model are the *gas* pedal position and *brake* pedal force. When the ICC is either off or being overruled, the gas and brake signals produced by the subject in the *mock-up* are passed on to the vehicle model. When the ICC is on, and not overruled, the vehicle model receives its gas and brake signal from the ICC *actuators*.

When the ICC is on, it calculates an acceleration reference *aref*. An inner control loop has the objective of realizing this desired acceleration as well as possible. The *acceleration controller* compares aref which the actual acceleration *a*, and calculates the controller output *cu*. The acceleration controller is of the PI type with anti-reset windup. Next, the *actuators* determine appropriate gas and brake signals from cu.

The signal aref is taken from either the *distance controller* output *aref_d* or the *speed controller* output *aref_v*. When a lead vehicle has been detected, indicated by the variable *target_found*, aref equals the most restrictive of aref_d and aref_v. When no lead car has been found, the ICC is in speed control mode and therefore aref equals aref_v.

Table AI Distance bar LEDs lighted as a function of the distance error de.

L1	L2	L3	L4	L5
red	red	yellow	green	green

de (%)	LEDs on
de < -23	L1
-23 ≤ de < -17	L1 + L2
-18 ≤ de < -11	L2
-11 ≤ de < -5	L2 + L3
-5 ≤ de < 6	L3
7 ≤ de < 13	L3 + L4
13 ≤ de < 19	L4
19 ≤ de < 25	L4 + L5
25 ≤ de	L5

The *I.R. sensor* produces the distance *dist* and relative speed *rs* to a lead vehicle when this distance is smaller than 120 m. In the simulator an ideal sensor has been realized in the sense that it has no delay or measurement noise.

The *distance controller* produces aref_d based on the relative speed *rs* and the *de*, the internally calculated percentage distance error to the reference distance. This reference distance is a linear function of the speed *v* and corresponds to a constant time headway of 1.5 s. The values for *de* and *rs* are used as indices in a two-dimensional look-up table to get aref_d. This table, which was developed using fuzzy control methods, has been made available for this experiment by Daimler-Benz.
The value of *de* also determines which of the five LEDs on the bar of the *distance display* are switched on: green lights indicate a distance larger than the reference distance and red lights mean too small a distance (see Table AI).

The *speed controller* is a simple P-type controller: its output is proportional to the difference between the actual speed *v* and the setpoint *vref*.

The speed controller and distance controller outputs are limited within the boundaries shown in Table AII.

Table AII Limits to controller outputs.

controller	lower limit (m/s^2)	upper limit (m/s^2)
distance controller	-1.8	1.2
speed controller	-1.0	1.0

The *Cruise Control Computer* keeps track of the state of the ICC, i.e. whether it is on, off, or overruled, and the reference speed *vref*. This is determined by the *switches* controlled by the driver and by the gas pedal position of the mock-up (when the gas pedal is released, the ICC switches off). The reference speed is shown by a continuous LED on the speedometer.

The messages from the roadside system arrive in the *receiver*. A maximum speed is shown as a flashing LED on the speedometer, and a *feedback* message to the driver is generated. If an intervening system is simulated, the received speed limit *v_lim* is passed on to the cruise control computer, where vref is limited to v_lim.

Conform the Daimler-Benz approach, two additional *sounds* were implemented to inform the driver about the state of the ICC. The first is a simple beep when the ICC is disengaged by means of the cruise control switch. The second is an alarm signal that is heard when the ICC detects a lead car driving so slowly that the maximum deceleration is not sufficient to avoid a collision, given the momentaneous distance and relative speed.

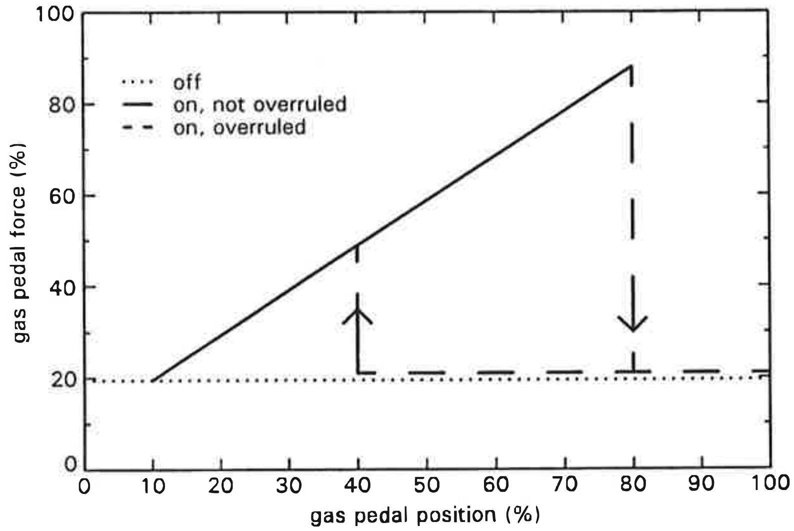


Fig. A2 Force-position characteristic of the gas pedal.

In order to make it clear to the driver whether the ICC is on, off, or overruled, the characteristic of the gas pedal was made dependent on the state of the ICC (*gas force*). The return force felt by the driver on the gas pedal is produced by a servo motor. The state-dependent characteristic is shown in Fig. A2. As long as the ICC is off, the force is constant at about 20% (where 100% corresponds to 185 N, the maximum force the servo motor can deliver). When the driver has switched the ICC on, this is felt as an increasing force when the gas pedal position is increased. As long as the pedal position remains between 10 and 80% the ICC stays on. Below 10% it automatically disengages. The ICC can be overruled by pressing the pedal position above 80%. Then the force drops to a lower, constant level. Because of a hysteresis in the characteristic, the driver now has the pedal range of 40 to 100% to override the system. Only when the position is lowered beneath 40% the system is no longer overruled, which if felt as an sudden increase of the pedal force.

When the driver engages the ICC while the gas pedal position exceeds 80%, he is immediately in the overrule mode and hence would feel no change in the pedal force. Therefore, an additional pulse with a period of 0.1 s was generated in this case.

APPENDIX B Specification of feedback messages

Variable Message Signs

VMSs were present at intervals of once every 500 m on the entire route. Above each lane there was a sign to indicate the maximum speed, and in between a sign to give the reason for that limit (queue or curve). Each of these signs was 1.65 m in width and 1.35 m in height. These dimensions exceed those of a real VMS, which was necessary to comply with the demand that they must be readable between 120 and 35 m distance (Rijkswaterstaat, 1993).

Basic in-vehicle feedback

In each configuration with roadside-to-vehicle communication, the basic feedback consisted of an acoustic signal ('beep') indicating when a new maximum speed had been received from a beacon, and a flashing LED on the speedometer to indicate that maximum speed visually.

Visual feedback

Visual feedback messages were displayed on a 11x8.5 cm colour television screen mounted to the right of the steering wheel. Two traffic signs could be showed simultaneously in colour on a dark background. The following configurations were used:

Table BI Visual feedback.

Scenario	Left symbol	Right symbol
100 km/h scenario	100 km/h speed limit	-
curve scenario	80 km/h speed limit	Sharp curve to the right
queue scenario	50 km/h speed limit	Traffic queue
standard	End of all restrictions1)	-

1) this sign was removed after 500 m, leaving the screen dark.

Acoustic feedback

The audio feedback messages were sampled. The following messages were used:

Table BII Acoustic feedback.

Scenario	Message (Dutch)	Message (English equivalent)
100 km/h scenario	'Maximum snelheid: honderd'	'Maximum speed: one hundred'
curve scenario	'Maximum snelheid: tachtig. Scherpe bocht naar rechts'	'Maximum speed: eighty. Sharp curve to the right.'
queue scenario	'Maximum snelheid: vijftig. File'	'Maximum speed: fifty. Traffic queue'
standard	'Einde snelheidsbeperking'	'End of speed restriction'

Haptic feedback

The feedback by means of the gas pedal consisted in a vibration on the gas pedal force, lasting 1 s, changing between zero and full force with a frequency of 15 Hz. This was followed by a verbal explanation, as indicated in Table BIII.

Table BIII Acoustic explanation after the haptic feedback.

Scenario	Message (Dutch)	Message (English equivalent)
100 km/h scenario	-	-
curve scenario	'Scherpe bocht naar rechts'	'Sharp curve to the right.'
queue scenario	'File'	'Traffic queue'
standard	-	-

APPENDIX C Questionnaire on subjective judgment

’ You have just driven a vehicle that had an Intelligent Cruise Control. Please indicate on the scales below what you think of the system.
There are five rating categories. If you agree completely with the description as given on the left-hand side, then tick the box at the extreme left. If you agree completely with the description at the right-hand side, tick the box at the extreme right. Tick other boxes in correspondence with what your judgment is with respect to the extremes. ’

My judgments of the ICC as I have experienced it are:

useful						senseless
pleasant						unpleasant
good						bad
effective						superfluous
nice						boring
desirable						undesirable
congenial						irritating
helpful						worthless
alerting						sleep-provoking