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Effects of Intelligent Cruise Control on driving behaviour: a simulator study

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J.H. Hogema and W.H. Janssen

SUMMARY

A driving simulator experiment was carried out to assess the effects of Intelligent Cruise Control (ICC) on driving behaviour. ICC is an in-vehicle system that automatically regulates a vehicle's speed and that is also capable of maintaining a proper following distance behind a lead vehicle. ICCs can only realize a moderate level of deceleration: in situations that require hard braking, the driver must take over control.

Two types of ICC were used: one where the subject had to keep his foot on the gas pedal while ICC was activated, and one where this was not necessary. During the experiment, subjects were confronted with several scenarios, varying from normal to critical. The main questions were: first, is there a difference between these ICC types in terms of acceptance and of reaction in critical situations, and second, when do subjects switch the ICC on and off with respect to the driving situation.

The results showed that ICC yields more consistent longitudinal control: in car-following situations, there is less variation in headway and in speed. It also appeared that when driving with ICC, subjects select a lower free-driving speed compared to their driving speed in the same scenario without ICC. In the critical scenarios where the subject had to take over control from the ICC, a later reaction was found especially in the first runs of the experiment. There was no difference between the foot-on-gas and the foot-off-gas ICC types in terms of driving behaviour. The questionnaire results, however, showed that subjects were highly in favour of the foot-off-gas type ICC, even though the overall judgements of both ICC types were positive.

Effecten van Intelligent Cruise Control op het rijgedrag: een simulatorstudie

J.H. Hogema en W.H. Janssen

SAMENVATTING

In een rijsimulator-studie zijn de effecten van Intelligent Cruise Control (ICC) op het rijgedrag onderzocht. ICC is een voertuigsysteem dat automatisch de snelheid regelt en bovendien in staat is om een passende volgafstand achter een voorligger te handhaven. ICCs kunnen slechts een beperkte deceleratie realiseren: in situaties waarin hard geremd moet worden moet de bestuurder de controle overnemen.

Er zijn twee ICC-typen onderzocht: een waarbij de proefpersoon zijn voet op het gaspedaal moest houden tijdens het rijden met ICC, en een waarbij dit niet hoefde. Tijdens het experiment werden de proefpersonen geconfronteerd met diverse scenario's, variërend van normaal tot kritisch. De belangrijkste vragen waren: ten eerste of er verschil was tussen deze ICC-typen in termen van reacties in kritische situaties en van acceptatie, en ten tweede wanneer de proefpersonen de ICC in- en uitschakelen in relatie tot de rijsituatie.

De resultaten lieten zien dat ICC resulteert in consistenter longitudinaal regelen: in volgsituaties is er minder spreiding in volgtijd en snelheid. Daarnaast bleek dat proefpersonen wanneer ze met ICC rijden een lagere vrije snelheid instellen vergeleken met hun rijsnelheid in hetzelfde scenario zonder ICC. In de urgente scenario's waarin de proefpersonen de controle van de ICC moesten overnemen werd vooral in de eerste ritten van het experiment een latere remreactie gevonden. Er was geen verschil tussen de ICC varianten voet-op-gas en voet-van-het gas in termen van het rijgedrag. Wel lieten de resultaten van de vragenlijsten zien dat de proefpersonen de ICC met voet-van-het-gas sterk prefereerden, waarbij overigens de algehele oordelen over beide ICC typen positief waren.

1 INTRODUCTION

Intelligent Cruise Controls (ICCs) are currently in development in the automotive industry, and their introduction on the market is expected within a few years. In addition to the conventional Cruise Control function of controlling a vehicle's speed at a driver-chosen value, an ICC is capable of maintaining a certain headway behind slower vehicles ahead. In this context, much effort is put into the development of Autonomous Intelligent Cruise Controls (AICCs), which do not depend on communication with other vehicles or with a roadside system. A restriction of the current prototypes is that they can only realise moderate deceleration levels, i.e. they cannot perform emergency braking. Consequently, in situations that require stronger decelerations than the ICC can produce, the driver will have to take over control from the ICC. ICC is intended to be a comfort device, assisting the driver in longitudinal vehicle control, but the driver remains responsible for the control of the vehicle.

Possible advantages of these systems on the individual driver level are an increased driving comfort and a reduction of workload. There may also be a positive effect on safety since in car-following situations, the ICC maintains a safe headway. On the other hand, a possible drawback in terms of safety is that prolonged driving with ICC could reduce the driver's alertness. In addition, it is not known how well drivers can perform their new task of monitoring the ICCs functioning, and especially recognize in time the urgent situations where they have to take over control from the ICC.

In an earlier study named IRISS-1 (Integration of Roadway and In-car Support and Safety Systems), Hogema, Van der Horst, and Janssen (1994) carried out a driving simulator experiment to study the effects of ICC on driver behaviour. In that experiment, the ICC was combined with a communication system that sent data regarding the current speed limit from the roadside to the vehicle. Two ICC modes were distinguished. In the informative mode, the information received was presented to the driver in some way, but it was left to him whether to adjust his speed. In the intervening mode, a received speed limit was automatically used as the reference speed which the ICC tried to maintain. The ICC used in this experiment was based on the Daimler-Benz prototype of AICC (Müller & Nöcker, 1992), using a target headway of 1.5 s. With one of the ICC types, subjects were confronted with several more or less critical driving situations. These were accompanied by an appropriate speed limit, which was presented both in-vehicle and on the roadside by means of Variable Message Signs (VMS). The main results were:

- The percentage of time headways smaller than 1 s is decreased by ICC, as can be expected from a system that tries to maintain a 1.5 s headway.
- However, a compensation effect was found: the intervening system yielded a speed reduction in the critical scenarios, but on the remaining, normal driving sections, subjects increased their speed.
- In the most critical scenario (a stationary traffic queue, where subjects had to take over control from the ICC and had to brake themselves to avoid a collision), subjects were found to react later when driving with ICC compared to the control condition without ICC.

- Subjective results from the experiment led to doubt on user acceptance of the gas pedal Man-Machine Interface used in the experiment. For reasons of safety, drivers had to keep their foot on the gas pedal when ICC was activated, which is not in line with current prototypes as developed by car manufacturers.

Thus far, only effects of ICC on an individual driver behaviour level were discussed. In addition to this, a large-scale introduction of ICC in traffic is likely to have an impact on a more aggregated level, especially on traffic performance and traffic safety. These issues are studied in another project under contract with the Dutch Ministry of Transport, Public Works, and Water Management, where several TNO institutes are working together on the development of the microscopic traffic simulation model MIXIC (Van Arem, Hogema & Verheul, 1995). This simulation tool offers the possibility to study the effects of AICC on traffic performance and traffic safety. In a recent study, MIXIC was applied for several penetration levels of AICC in traffic (Van Arem et al., 1995). For this purpose, a new sub-model was added to the driver model to describe when a driver takes over control from the AICC in critical situations, and when the driver subsequently re-engages the cruise control. However, only a "first-guess" sub-model could be used here because of a lack of knowledge on how drivers actually react in such situations.

Therefore, under contract with the Dutch Ministry of Transport, Public Works, and Water Management, the TNO Human Factors Research Institute (HFRI) carried out a new empirical study on the effects of ICC on driving behaviour (IRISS-2). The main questions (resulting from both the IRISS-1 and the MIXIC study) were:
1 when comparing an ICC where the driver has to keep his foot on the gas pedal with an ICC where this is not required, is there a difference in the (brake) reaction in critical situations, and is there a difference in user acceptance, and
2 in critical situations, when do drivers disengage the ICC and when do they re-engage it.

In order to have full control over the experimental conditions, the study was carried out in the TNO driving simulator. Furthermore, in the driving simulator, critical situations can be studied without endangering the subjects.

2 METHOD

2.1 Experimental conditions and scenarios

Two types of ICC were compared in this study:
- The first ICC type only functioned as long as the driver kept his foot on the gas pedal ("foot-on-gas" type); releasing the gas pedal automatically switched the ICC off.
- The second ICC type functioned normally when the driver removed his foot from the gas pedal ("foot-off-gas" type). Pressing the brake pedal automatically switched the ICC off.

Additionally, both ICC types could be disengaged by means of a switch (see § 2.2).

Two traffic conditions were defined, viz. a car-following and a free-driving condition. In the car-following condition, there were ten cars ahead of the subject (five in each lane) which could not be overtaken. The experimental runs were composed mainly of normal driving situations without a special speed limit or extreme manoeuvres of the other traffic. This was the standard scenario with an implicit speed limit of 120 km/h. Every now and then, a subject would be confronted with a more or less critical scenario:

1 a 100 km/h speed limit for no apparent reason,
2 a 80 km/h speed limit because of a sharp curve in the road, designed such that it was rather difficult to negotiate at speeds over 80 km/h.
3 a 50 km/h limit because of a stationary traffic queue (such that the driver must take over control from the ICC in order to avoid a collision),
4 a 50 km/h limit because of a moving traffic queue (such that the ICC can handle the situation).

These four scenarios were all included once in each run, and hence there were 5 standard '120 km/h' parts in all in each run. Speed limits and the reason for the speed limits ('curve' or 'queue' symbol) were displayed on Variable Message Signs (VMS) above the road.

In the car-following condition, other cars in the simulation executed the following manoeuvres in three of the five standard parts in each run:

5 the lead cars suddenly braked hard (so that the subject had to take over control from the ICC in order to avoid a collision)
6 the lead cars suddenly braked moderately (in such a way that the ICC could deal with the situation)
7 a car in the other lane merged between the subject and his initial lead car.

In the free-driving condition, the following event occurred in three out of the five '120 km/h' parts of each run:

8 a single, slower lead car would appear. The subject could either overtake or follow this car.

A more detailed description of the scenarios is given in Appendix B.

2.2 Apparatus

The TNO driving simulator

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

- The *supervisor* computer (PC, Pentium 100 MHz microprocessor) which had 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 calculated the momentaneous position and heading of the simulated vehicle with the characteristics of a Volvo 240.
- The *Computer Generated Image* system (CGI, Evans & Sutherland ESIG 2000), which generated real-time images (refresh frequency 60 Hz, update frequency 30 Hz).
- The *sound generator system*. This was a sampled sound system using an AKAI S3200 sampler (noise of engine, wind, and tires).

During the experiment, the subject was seated in a fixed base mock-up of a Volvo 240 and had all normal controls (steering wheel, accelerator, brake, etc.) at his disposal. Based on the control signals, the vehicle model computed 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 was given to the driver by means of an electrical torque engine, and of sound by the sound generator system. The momentaneous position and heading angle were transmitted via the supervisor to the visual scene computer. The three-channel CGI system computed the visual scene as seen from the position of the driver. This image was projected on a screen in front of the mock-up by means of three high-resolution BARCOGRAPHICS 801 projectors (total visual angles: 120° horizontally, 35° vertically). The experimenter was seated in a room next to the mock-up room, where he has access to the control system. Communication with the subject was possible by means of an intercom.

The logic of the Intelligent Cruise Control

As in IRISS-1, 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). In the absence of a leading vehicle, the ICC provides *speed control* in the same manner as a conventional cruise control. In this case the control loop aims at keeping the actual speed of the vehicle equal to the reference speed set by the driver. When a lead vehicle was detected the ICC switches automatically to *distance control*. In this mode the headway was controlled at an appropriate value (in the current experiment a time headway of 1.5 s). When the ICC was on and the subject was closing in on a lead car so fast that the ICC could not cope with the situation, an alarm sounded.

As described in § 2.1, two types of ICC were used. The first ICC type ("on-gas") only functioned as long as the subject kept his foot on the gas pedal: releasing the gas pedal automatically switched the ICC off. This is the same approach as followed in IRISS-1. The subject could overrule this type of ICC at all times by pushing the gas pedal deeper than 80% of the full range. The second ICC type ("off-gas") did not require the driver to keep his foot on the gas pedal when the ICC was active (as in the Daimler-Benz AICC prototype). The driver could always overrule this ICC type by pressing the gas pedal deeper than the gas actuator position as determined by the ICC algorithm. Pressing the brake pedal automatically disengaged the "off-gas" ICC.

Three ICC states were distinguished: "on-and-not-overruled", "on-but-overruled", and "off". In the "on-and-not-overruled" state, the ICC controlled the car's speed. There may be situations 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 could be achieved by pressing the gas pedal firmly, causing the ICC to switch to the "on but overruled" state. In this state, the gas pedal position produced by the driver determined the car's speed, but the ICC algorithm was 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 released the gas pedal the ICC automatically returned to the "on-and-not-overruled" state.
When the driver wanted to reduce speed in the "on-and-not-overruled" state, he could do so by adjusting the ICC's set speed or by switching the ICC "off". Once the ICC was "off", the ICC system was totally disengaged and it could 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 set speed by pressing the gas pedal.

The ICC could be switched on and off by means of the *ICC switch* attached to the steering column (see Fig. 1). Its *set* function switched the ICC on and took the current speed as the reference speed. The *resume* function could also be used to switch the ICC on: then the earlier reference speed was used again. Once the ICC was on, the driver could adjust the reference speed in two ways. The *accelerate/decelerate* function of the ICC switch gradually increased or decreased the reference speed, whereas the *speed select pushbutton* (Fig. 1) could be used to increase or decrease the reference speed in steps of 10 km/h. The reference speed was displayed in multiples of 10 km/h by a continuous LED on the speedometer.
When a lead vehicle was detected, a five-segment LED bar on the dashboard gave an indication of the distance to the lead car: red LEDs meant that the distance was too small, an orange LED meant the distance was normal, and green LEDs indicated too large a distance with respect to the 1.5 s headway setpoint.

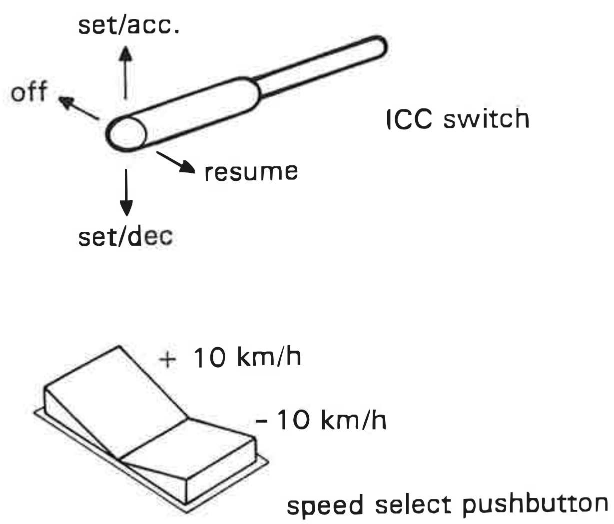

Fig. 1 Control switches of the ICC.

The ICC used in the current study closely resembles the Daimler-Benz prototype in terms of the controls and displays and of the control algorithms used. The Daimler-Benz prototype allows the driver to release the gas pedal when the AICC is activated, corresponding to the "off gas" ICC type in the current experiment. A difference between the simulator ICC and real ICCs is that an ideal sensor was implemented in the simulator in the sense that it had no delay or measurement noise. Additionally, it always correctly detected a lead car in the driver's lane when this lead car was within the sensor range, even when it was stationary. In reality, the sensor beam might see past a lead car for example in a sharp curve, and in many prototype ICCs, stationary obstacles are ignored. For a more detailed technical description of the ICC, the reader is referred to Appendix A.

2.3 Subjects

Twelve male subjects participated in the experiment. They all had a driving licence for at least three years, they were all younger than 60 and they drove at least 10 000 km a year. None of the subjects had participated in the IRISS-1 experiment. The subjects were paid for their participation. Since no interactions were expected between sex and the experimental variables, only male subjects were recruited as usual in this type of research (see also Janssen et al., 1992, and Kaptein et al., 1995). This served to reduce the variability of the measurements and consequently increase the statistical power of the experiment.
In IRISS-1, where 6 subjects per experimental group had been used, some relevant results failed to reach significance and merely yielded trends. Because of this, it was considered necessary to have more statistical power in the current study. Therefore, a within-subjects design was used instead of a between-subjects design, with a total of twelve subjects. This had the additional advantage that it had good balancing possibilities with the two ICC conditions and two traffic conditions.

2.4 Procedure

Before starting the first run, each subject was given general verbal instructions. He was informed that he would be driving on a motorway and that everyday traffic situations would be encountered. He was asked to move on a bit, but to adjust his behaviour to the circumstances such that traffic safety was not endangered.

Each subject completed three separate blocks, corresponding to the three ICC conditions: ICC type "on-gas", ICC type "off-gas", and no ICC. The order of presentation of these ICC conditions was balanced over subjects. Furthermore, each block consisted of two runs: a free-driving and a car-following run (in balanced order over subjects).

Before the first ICC block started, the experimenter gave operating instructions for the specific form of ICC the subject would encounter. The experimenter first verbally explained how to operate the ICC. It was explicitly stated that the ICC is not an 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.

Next, an instruction run 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. Then a training run was given to let the subject get accustomed to driving with the ICC. After that, the experimental run started.
If the first block of a subject consisted of the "no ICC" condition, he was given a training run without ICC first to let him get accustomed to driving the simulator.

Before a subject's second ICC block was started, the experimenter gave instructions for ICC type to be used in this block. As before, an instruction run and a training run were given before the experimental runs were started.

In the car-following runs, the other traffic obeyed to the explicit speed limits of the scenarios. In the standard scenario, however, they drove 110 km/h to ensure subjects would stay in a car-following situation even when they did not want to exceed a speed of 120 km/h. The other cars behaved according to a car-following model which was based on the MIXIC driver model (Van Arem, Hogema & Verheul, 1995). Their maximum acceleration decreased as a function of speed, in such a way that it was always smaller than the maximum acceleration of the driving simulator's vehicle model. Therefore, subjects could always follow the lead cars if they wanted to.

Each run started on the right lane at almost standstill. In the car-following condition, there were ten other cars present (five in each lane). The run then consisted of five standard sections interchanged with the four scenarios that involved explicit speed limits (Scenarios 1–4); the order of presentation of the latter was randomized. In the car-following condition, the other cars would carry out a the manoeuvres of Scenarios 5–7 in three out of the five standard sections. The occurrence of these scenarios was randomized. In the free-driving condition, a single slower lead car (Scenario 8) appeared in three out of the five standard sections (randomized as well).

After having completed the last run with one ICC type, subjects filled out a questionnaire about their subjective impressions of that ICC (see Appendix C). The questionnaire, which had been developed and used in earlier research (Janssen, Brookhuis & Kuiken, 1993; Hogema, Van der Horst & Janssen, 1994) comprises nine specific questions, each allowing a rating on a five-point scale. Apart from this, subjects were asked to indicate their overall level of satisfaction with the specific feature of having to keep the foot on the gas pedal or not. This was also done on a five-point scale, running from definitely negative to definitely positive. Finally, after having completed the final run, subjects judged a number of aspects of the modus operandi that were common to both forms of ICC, notably:
a) the adequacy of the control of speed
b) the adequacy of the control of headway
c) the ease of using the system, in terms of switches and dials
d) the quality of the provision of in-vehicle information on speeds and headways.

2.5 Data collection and analysis

During the experimental runs the following variables were measured:
- longitudinal position of the subject's vehicle (m)
- speed (m/s),
- gas pedal position in the mock-up (%),
- brake pedal force in the mock-up (N),
- 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, computed gas and brake actuator position).

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. A 5-s time headway criterion was used to distinguish free-driving from car-following situations.
- 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:
- *general ICC usage*: ICC state, ICC disengaging/activation, occurrence of alarm;
- *free-driving speed*: mean and standard deviation (s.d.), 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, mean headway, and s.d. of the speed in car-following situations;
- *approaching queues* and *braking lead cars*: 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}).
- *merging lead cars*: following distance at four separate instants describing the manoeuvre.

The results were tested for statistical significance by means of analyses of variance (ANOVA).

The questionnaire results were analyzed in two ways. First, in the 'raw' analysis, ratings (transformed to values between -2 and $+2$, i.e., from absolutely negative to absolutely positive) were simply averaged over subjects for each form of ICC. Second, in the "composite" analysis the questionnaire ratings were subjected to a dimensional analysis on the basis of earlier findings from Janssen, Brookhuis, and Kuiken (1993), and Van der Laan, Heino, and De Waard (1996). Basically, these authors have shown that two factors ("Perceived Usefulness" and "Perceived Comfort") are sufficient to cover the original nine rating scales. They also showed that the factor score for "Perceived Usefulness" may be obtained by simply averaging the ratings on the "Useful", "Good", "Nice", "Congenial", and "Alerting" scales, whereas the factor score for "Perceived Comfort" is the average score for the remaining scales. This method for obtaining Perceived Usefulness and Perceived Comfort scores is different from the method used in IRISS-1 (see Hogema, Van der Horst & Janssen, 1994).

3 RESULTS

3.1 Overall ICC usage

The distribution of ICC states over all scenarios is given in Table I for ICC type "on-gas" and "off-gas", separately. The results show that subjects did behave according to the instructions, i.e. they did use the ICC most of the time. To test whether the usage differed for the ICC types, the percentages were transformed using an arcsine function (Winer et al., 1991) and compared using t-tests. Only for the "on" state, the difference between the ICC types was significant [$p<0.001$]: the "off gas" type ICC was engaged more than the "on gas" type.

Table I Percentage of time of each ICC state as a function of ICC type (average over all subjects).

ICC state	ICC type "on-gas"	ICC type "off-gas"
on (not overruled)	86.3	91.4
overruled	4.3	2.4
off	9.4	6.2

Table II shows the distribution of ICC states as a function of driving condition (free driving vs. car following). T-tests on the transformed percentages showed that ICC is overruled more often in free-driving situations than in car-following situations [$p<0.001$]. In fact, the ICC is hardly overruled in the car-following condition. This can be attributed to the fact that in car-following situations, it is not possible to maintain a continuous overrule state: overruling the distance controller results in a continuously decreasing following distance and this would eventually lead to a collision.
Additionally, the percentage of ICC in the "off" state was larger in the car-following condition than in the free-driving condition [$p<0.05$]. This is probably caused by the

experimental setup: the most critical scenarios, where the ICC has to be switched off to avoid a collision, occurred in the car-following condition (queues, braking lead cars).

Table II Percentage of time of each ICC state as a function of driving condition (average over all subjects).

ICC state	free driving	car following
on (not overruled)	86.9	90.4
overruled	6.2	0.7
off	6.9	8.9

The distribution of ICC states as a function of speed limit is shown in Table III. This again confirms that the ICC was in the "on" state most of the time. Three separate ANOVAs were carried out (one for each state) on the transformed percentages, using speed limit as the only factor. This revealed some differences among the speed limit conditions. A Newman-Keuls post-hoc test showed that the percentage of time in the "overruled" state was larger in the 50 and 120 km/h conditions than in the 80 and 100 km/h conditions [all $p<0.001$]. Still, the "overruled" state occurred infrequently compared to the "on" state. Further, in the 50 km/h condition, the ICC was in the "off" state more often than in the other speed conditions [$p<0.001$]. This can be attributed to the (stationary) queue scenario of the 50 km/h condition, where the ICC had to be switched off.

Table III Percentage of time of each ICC state as a function of speed limit (average over all subjects).

ICC state	50 km/h (queue)	80 km/h (curve)	100 km/h	120 km/h (standard)
on (not overruled)	72.1	86.0	99.6	91.4
overruled	3.1	0.3	0.0	3.8
off	24.8	13.6	0.4	4.8

Disengaging the ICC

As can be seen in Table IV, the ICC type "on-gas" was switched off more often than the "off-gas" ICC [$\chi^2=21$, $N=2$, $p<0.001$]. The ICC is switched off more often by using the pedal (either the gas or the brake pedal, depending on the type of ICC) than by using the Cruise Control switch. The number of ICC deactivations using the pedal is higher for "on-gas" than for "off-gas" ICCs [$\chi^2=29$, $N=2$, $p<0.001$]. There was no difference between the ICC types in the number of switch deactivations [$\chi^2=1.7$, $N=2$, $p<0.2$].

Table IV Average number of times per run the ICC was switched off (by ICC type and by switching method).

Switching method	ICC type "on-gas"	ICC type "off-gas"
using pedal	5.7[1)]	2.5[2)]
using switch	0.5	0.8
total	6.2	3.3

[1)] by releasing the gas pedal
[2)] by pressing the brake pedal

The distribution of accelerations at the moment of ICC deactivation has a median of -0.5 m/s^2 and a 15^{th} percentile of -1.2 m/s^2. This shows that subjects typically took over control before the ICC reached its maximum deceleration of 1.8 m/s^2.

Activating the ICC

To investigate the relationship between the driving situation and the (re-)activation of the ICC, an overview of all activations was made. On average, the ICC was activated 5.6 times in each run. Of all activations, 65% took place in a car-following situation (time headway < 5 s). These were examined more closely in terms of headway, distance, speed difference and TTC. The headway distribution was asymmetrical with a 85^{th} percentile of 2.63 s, a median of 1.49 s, and a 15^{th} percentile of 1.03 s. As will be seen in Section 3.3, the 15^{th} percentile of the headway distribution for the condition with no ICC was smaller (0.85 s). Apparently, there was a tendency of avoiding ICC activations at small headways (< 1 s). The median of the distribution of the speed difference at the moment of ICC activation was -0.3 m/s (where a negative speed difference indicates an increasing following distance). The 15^{th} and 85^{th} percentile were -2.0 and $+0.7$ m/s, respectively. Of all ICC activations in a car-following situation, only 37% occurred with a positive speed difference. This indicates a preference to activate ICC when there is no collision course. The distribution of acceleration at the moment of ICC activation had a 15^{th} percentile of -0.48 m/s^2 and a 85^{th} percentile of 0.62 m/s^2. According to a two-sided t-test, the mean (0.09 m/s^2) was significantly larger than 0 [$t=2.18$, $df=267$, $p<0.05$]. Apparently, subjects avoided activating the ICC while strongly accelerating or decelerating.

Anti-collision warnings and "collisions"

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 sounded (see § 2.2). This happened in the "stationary queue" and "hard braking lead cars" scenarios only. These two most urgent scenarios together occurred on average 1.5 times in each run, whereas the average number of actual alarms per run was 0.7. A Chi-square test revealed no significant effect in the total number of alarms between ICC types "on-gas" and "off-gas" (16 and 17 alarms, respectively) [$\chi^2=0.03$, $N=2$, $p<0.9$].

In the runs without ICC, no collision warning was given. However, applying the warning criterion off-line to the measurements of these runs yielded a total of 12 theoretical alarms. This does not significantly deviate from the number of alarms found with ICC [$\chi^2=0.93$, $N=2$, $p<0.6$].

In the entire experiment, three "collisions" occurred: one with ICC "on-gas" and two without ICC. All "collisions" occurred in a first experimental run. These numbers are so small that no conclusions can be drawn about possible effects of ICC condition on the occurrence of collisions [$\chi^2=2.0$, $N=2$, $p<0.36$].

To summarise these findings:
- The "off gas" ICC was more in the "on" (but not overruled) state than the "on gas" ICC, and it was also switched off less frequently.
- Subjects typically took over control from the ICC before it reached its maximum deceleration.
- Subjects avoided activating the ICC at small headways and while strongly accelerating or decelerating.
- No effects of ICC condition were found on the number of anti-collision warnings or on the number of "collisions".

3.2 Free driving

The analysis of free-driving speeds was carried out on all free-driving sections of the runs, i.e. where there were no lead cars, or the time headway was longer than 5 s. When regarding free-driving speed choice, the process of speed adjustment when encountering a new speed limit is less relevant. Therefore, a zone around each VMS that showed the subjects a new speed limit compared to the previous VMS was excluded from the analysis (100 m before until 300 m after such a VMS). Similarly, the first 120 s of each run were discarded, since this included the acceleration from standstill to the desired free-driving speed.

An ANOVA was carried out on the mean free-driving speed using the factors ICC condition and speed limit (50-80-100-120). Both factors were significant [$F(2,22)=10$, $p<0.001$, and $F(3,33)=92$, $p<0.001$, respectively]. There was no significant interaction [$p<0.16$]; see Figs 2 and 3. Note that only free-driving sections of the runs were included in this analysis; for the queue condition this is only the part where the queue has moved to the hard shoulder. This explains how in the queue condition a mean free-driving speed of 77 km/h could be realised.

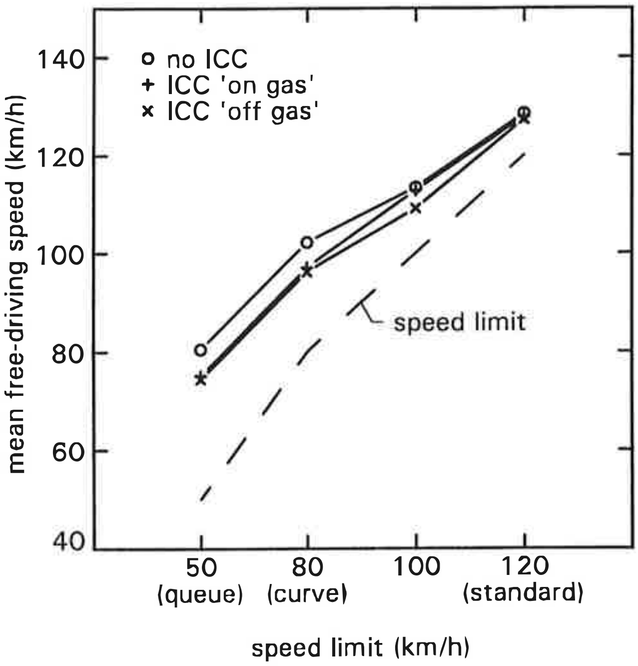

Fig. 2 Mean free-driving speed as a function of ICC condition and speed limit.

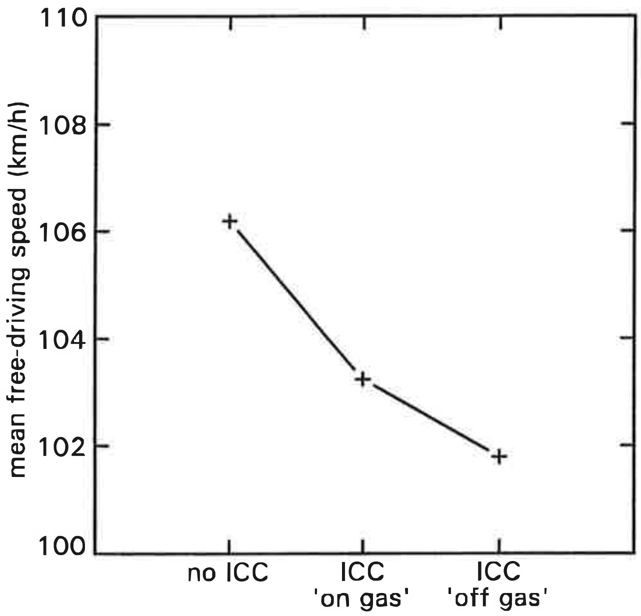

Fig. 3 Mean free-driving speed as a function of ICC condition.

A Newman-Keuls post-hoc test revealed that the mean free-driving speed in both ICC conditions were lower than in the no-ICC condition [$p<0.01$ and $p<0.001$, respectively]. There was no significant difference between the two conditions with ICC [$p<0.16$].

The standard deviation (s.d.) of the free driving speed was determined for each run over the same periods as the mean. An ANOVA was carried out on this s.d. using the factors ICC and speed limit. Only the factor speed limit was significant [$F(3,33)=48$, $p<0.001$]. A Newman-Keuls post-hoc test revealed that the s.d. in the 50 km/h sections was significantly higher than in the other sections [all $p<0.002$]; there was no significant difference among the s.d.'s at 80, 100 and 120 km/h [all $p<0.4$].

The results discussed thus far were obtained without differentiating between ICC states (on/off/overruled). A second set of ANOVAs was carried out in which only periods with activated ICC were included. The effects found in these analyses did not deviate from those discussed above.

To summarise these results, the mean free-driving speed was lower when driving with ICC compared to driving without ICC. Differences between the on-gas and the off-gas type ICC were not found.

3.3 Car-following behaviour

The first car-following parameter analysed was the percentage of time subjects were in a car-following situation (i.e., had a time headway of less than 5 s). An ANOVA using the factors ICC condition and speed limit revealed only an effect of speed limit [$F(3,33)=19$, $p<0.001$]: in 50 km/h zones, subjects were more often in a car-following situation (65%) compared to the other speed limits (mean around 51%). This is caused by the scenarios themselves and not by a behavioural change: in all queue scenarios (speed limit 50 km/h), there were lead cars, even in the free-driving runs.

Next, regarding only car-following situations, the percentage of time with a headway less than 1 s was also analysed by means of an ANOVA. The factors used were ICC condition and speed limit. There was only an effect of ICC condition [$F(2,20)=23$, $p<0.001$], see Fig. 4. The presence of ICC reduced the percentage of short headways drastically from 29% to about 2%. A Newman-Keuls post-hoc test revealed no difference between both ICC types [$p<0.8$].

In car-following situations, the speed choice of the follower is determined by the speed of the lead car. The s.d. of the speed during the runs, however, may be influenced by the presence of ICC. To investigate this, the s.d. of the speed within each run was determined for the car-following situations and an ANOVA was carried out on this s.d. using the factors ICC condition and speed limit. Both factors were significant [$F(2,18)=8.5$, $p<0.005$, and $F(3,27)=360$, $p<0.001$]; there was no interaction (see Fig. 5). According to a Newman-Keuls post-hoc test, the s.d.'s for ICC type "on-gas" and "off-gas" (7.1 and 6.4 km/h, respectively) are lower than the s.d. without ICC (8.1 km/h) [$p<0.02$ and $p<0.005$, respectively]. There was no significant difference between the ICC types [$p<0.16$].

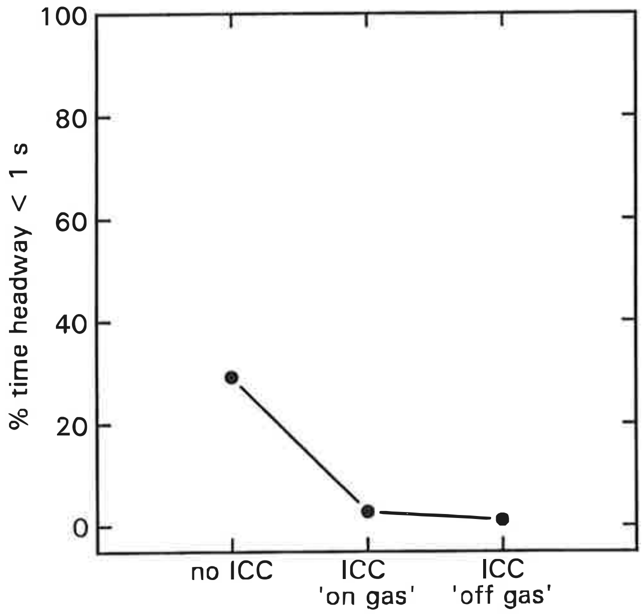

Fig. 4 The percentage of time headway < 1 s (over all following situations) as a function of ICC condition.

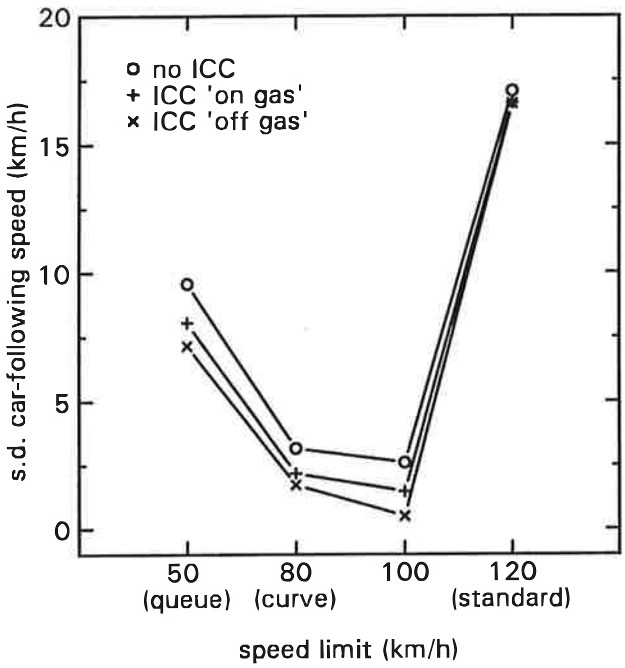

Fig. 5 Standard deviation of the speed within runs in car-following situations as a function of ICC condition and speed limit.

Fig. 6 shows the distribution of headways in following situations (all subjects and all speed limit levels together) for the three separate ICC conditions. This clearly shows that in both conditions with ICC, the distribution becomes more concentrated around the ICC's target headway of 1.5 s compared to the condition without ICC.

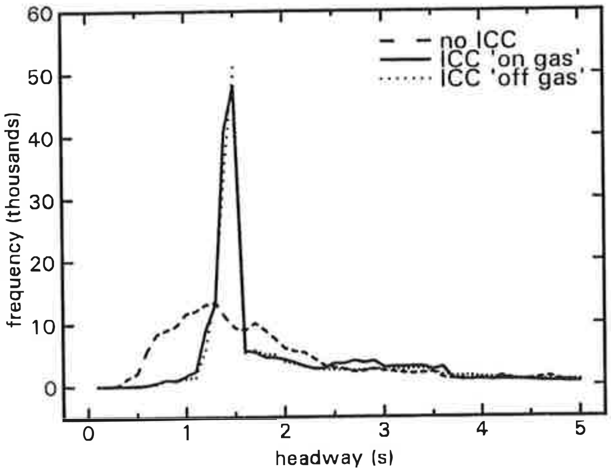

Fig. 6 Distribution of headway as a function of ICC condition.

The headway distributions for the conditions with ICC show that apparently, the ICC eliminates headways smaller than 1.5 s more effectively than headways larger than 1.5 s. A further in-depth analysis showed that with ICC, headways larger than the 1.5 s target headway occurred because of the ICC reference speed selected by the subject. When the ICC's reference speed was set at a speed that was equal to, or lower than the lead car's speed, the ICC's speed controller dominated the distance controller and consequently any headway larger than 1.5 s can result. From the distributions of Fig. 6, the characteristics as shown in Table V were derived.

Table V Characteristics of headway distribution as a function of ICC condition.

	no ICC	ICC on gas	ICC off gas
15th percentile	0.85 s	1.31 s	1.31 s
median	1.47 s	1.47 s	1.47 s
85th percentile	2.77 s	2.93 s	3.04 s

Finally, the mean headway during following situations was analysed by means of an ANOVA using the factors ICC condition and speed limit. The mean following headway without ICC was 1.7 s, and with ICC 1.9 s (averaged over both ICC types). There was no significant effect of ICC condition [$F(2,20)=1.4$, $p<0.3$].

In short, the results showed that:

- ICC drastically reduced the percentage of short time headways (< 1 s),
- ICC resulted in a more concentrated headway distribution around its target headway,
- the mean headway was not influenced by ICC, and
- differences between the on-gas and the off-gas type ICC were not found.

3.4 Approach manoeuvres

The *stationary traffic queue* scenario was designed such that during the approach, drivers had to disengage the ICC and brake themselves to avoid a collision. As expected, the results showed that in all ICC runs, the cruise control was switched off in each stationary queue scenario.

In the *driving queue* scenario, on the other hand, the ICC could cope with the situation. Nevertheless, subjects took over control in 69% of these scenarios when driving with ICC. With ICC type "on-gas", the ICC was disengaged more often than with ICC type "off-gas" [ICC disengaged in 83% and 54% of the driving queue scenarios, respectively; $\chi^2=4.8$, $N=2$, $p<0.05$], in line with the natural reaction of precautiously releasing the gas pedal.

3.4.1 Approaching queues in a free-driving situation

In the free-driving approaches to the traffic queues that were started with the foot on the gas pedal (i.e. ICC type "on-gas" or no ICC), the gas pedal was released in 47 out of 48 times. Of these releases, 83% had occurred before the subject passed the first VMS indicating the traffic queue, which shows that apparently the VMS information is used in the decision to switch the ICC off.

An ANOVA was carried out on $Dist_{gas}$ using the factors ICC condition (type "on-gas" and no ICC; for the "off-gas" type the foot was off the gas pedal by default) and queue condition (stationary and driving). There was a significant effect of ICC type: the mean $Dist_{gas}$ was smaller for ICC type "on-gas" than for the condition without ICC [334 m and 437 m, respectively; $F(1,10)=11$, $p<0.01$]. In the stationary queue condition, $Dist_{gas}$ was significantly smaller than in the moving queue condition [358 and 413 m, respectively; $F(1,10)=8.6$, $p<0.05$].

The same ANOVA was carried out on TTC_{gas}. There was a significant effect of both ICC condition [$F(1,10)=12.8$, $p<0.01$] and queue condition [$F(1,10)=9$, $p<0.05$]; see Fig. 7.

Next, ANOVAs were carried out on $Dist_{br}$, TTC_{br} and TTC_{min}, all using the factors ICC condition (both ICC types and no ICC) and queue condition (stationary and driving). None of these revealed an effect of ICC condition [$p<0.6$, $p<0.7$ and $p<0.3$, respectively]. Only the ANOVA on TTC_{min} revealed an effect of queue condition, showing that the stationary queue was more critical than the moving queue (mean TTC_{min} 3.8 and 8.5 s, respectively) [$F(1,10)=117$, $p<0.001$].

It was suspected that during the experiment, subjects may have learned to recognize the critical scenarios, and as a result of that adjust their behaviour. Therefore, the same dependent variables were analysed by means of an ANOVA using only the first experimental block, which turned "ICC condition" into a between-subjects variable (4 subjects per ICC condition). The queue condition remained a within-subjects variable. The results for $Dist_{gas}$ and TTC_{gas} did not deviate from the results presented above. The results for $Dist_{br}$ revealed a trend of ICC condition [$F(2,7)=3.4$, $p<0.1$]: a post-hoc test showed that $Dist_{br}$ was larger without ICC (399 m) than with ICC types "on-gas" and "off-gas" (284 and 313 m, respectively). There was no difference between the two ICC types [$p<0.6$]. Similar results were found for TTC_{br} and TTC_{min}, see Fig. 8.

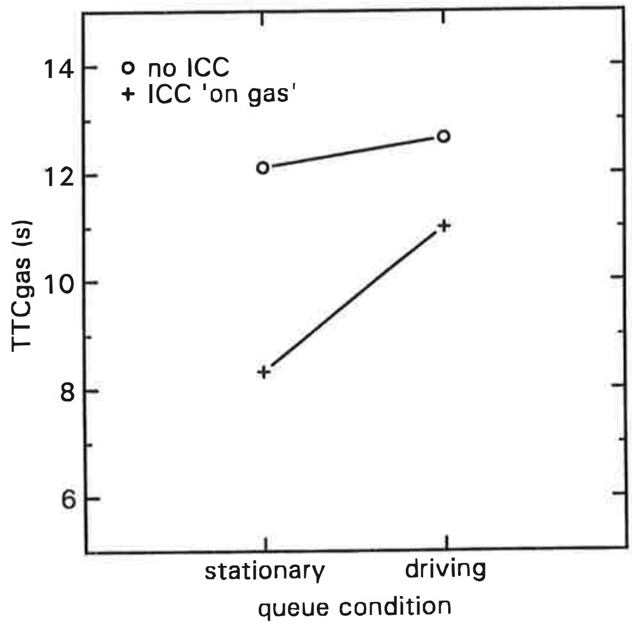

Fig. 7 TTC at the moment the gas pedal is first released as a function of ICC condition and queue condition (free-driving approach).

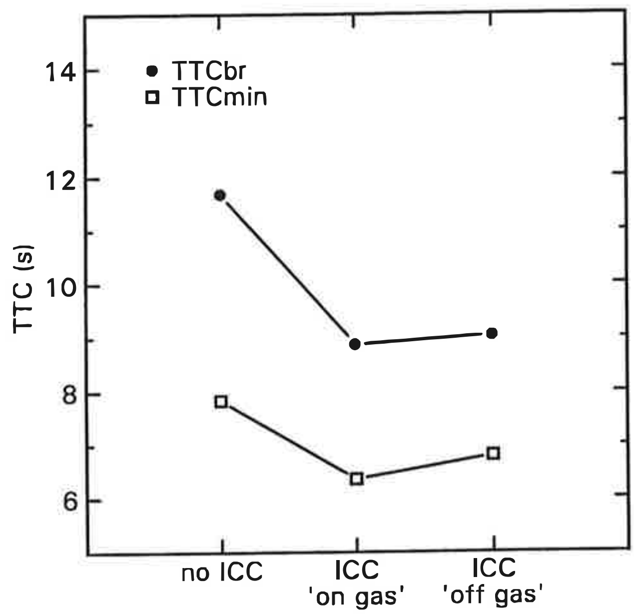

Fig. 8 TTC_{br} and TTC_{min} as a function of ICC condition (free-driving approach, first block only).

To summarize these results:

- The gas pedal was released later in the ICC type "on-gas" condition compared to the condition without ICC, both in terms of distance and in terms of TTC.

- When looking at all three blocks, there were no effects of ICC condition on $Dist_{br}$, TTC_{br} or TTC_{min}. When only the first block of each subject was used in the analysis, there were trends showing a later reaction for ICC (both types) compared to the condition without ICC; no differences between the ICC types were found.

3.4.2 Approaching queues in a car-following situation

In the approaches to the traffic queues in a car-following situation that were started with the foot on the gas pedal (i.e. ICC type "on-gas" or no ICC), the gas pedal was released in 45 out of 48 times. Of these releases, 87% had occurred before the subject passed the first VMS indicating the traffic queue, and 33% before the lead cars started to brake. This means that for these 33%, there was no collision course yet at the moment the drivers released the gas pedal, and therefore TTC_{gas} was not defined in these cases.

An ANOVA on $Dist_{gas}$, using the factors ICC condition (ICC type "on-gas" or no ICC) and queue condition, did not reveal any effect of the independent variables. The overall mean $Dist_{gas}$ was 58 m. An ANOVA on TTC_{gas} could not be carried out because there was no collision course, and hence no TTC, in too many cases.

ANOVAs on $Dist_{br}$ and TTC_{br}, both using the factors ICC condition (ICC type "on-gas" or no ICC) and queue condition, did not reveal any significant effect. After removing two outliers, an ANOVA on TTC_{min}, using the factors ICC condition (both ICC types and no ICC) and queue condition, showed an effect of queue condition [$F(1,8)=39$, $p<0.001$], see Fig. 9. There was also an interaction [$F(2,16)=3.2$, $p<0.1$].

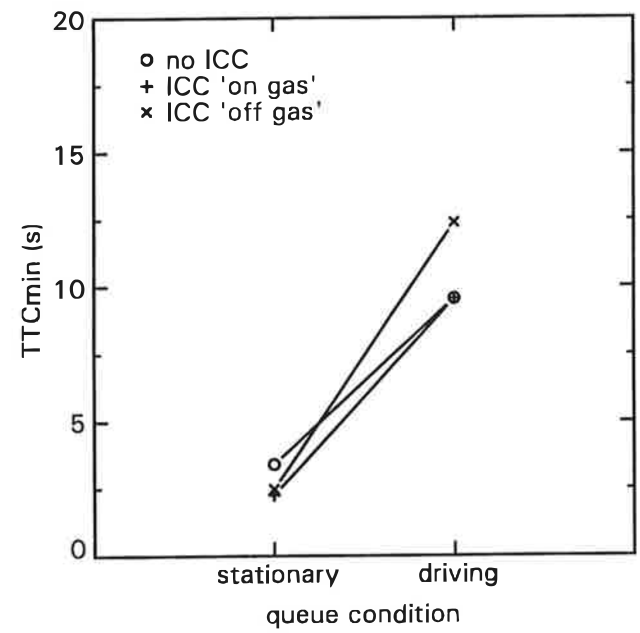

Fig. 9 Minimum TTC over the entire approach manoeuvre as a function of ICC condition and queue condition (following approach).

A post-hoc test showed that there was no difference between the ICC conditions in the stationary traffic queue condition [all $p > 0.4$]. In the driving queue condition, however, the mean TTC_{min} for ICC type "off-gas" was significantly higher than for the other ICC conditions [$p < 0.05$]. This only occurred in the driving queue condition, where all TTC_{min} values are far from critical regardless of the ICC condition.

Further ANOVAs using only the first experimental block did not reveal additional effects or interactions.

In short, the only significant difference found here between ICC conditions consisted of an interaction showing that in the (non-critical) approach to the driving queue, TTC_{min} was higher for the off-gas ICC than for the other ICC conditions.

3.5 Braking lead cars

The "hard braking lead cars" scenario was designed such, that subjects had to deactivate their ICC to avoid a collision. As expected, the ICC was switched off in each of these scenarios. In the "moderately braking" scenario, the ICC was deactivated in 71% of the cases, even though the ICC could cope with the situation.
An ANOVA was carried out on $Dist_{gas}$ using the factors ICC condition (type "on-gas" and no ICC; for type "off-gas" the foot was off the gas pedal by default) and braking condition (hard and moderate braking). There were no effects or interactions; the mean distance at the moment the gas pedal was released was 63 m.
An ANOVA on TTC_{gas}, using the same factors, revealed an effect of braking condition [$F(1,9)=11$, $p<0.01$] and a trend of ICC condition [$F(1,9)=3.7$, $p<0.1$], see Fig. 10. This indicates that subjects initiated their first reaction slightly later with the ICC type "on-gas" compared to the situation without ICC.

Next, ANOVAs were carried out on $Dist_{br}$ and on TTC_{br} using the factors ICC condition (both ICC types and no ICC) and braking condition (hard and moderate braking). These revealed no effects or interactions.

Finally, an ANOVA was carried out on TTC_{min} using the factors ICC condition and braking condition. This only revealed an effect of braking condition [$F(1,10)=64$, $p<0.001$]. As expected, the hard braking condition yielded a smaller mean TTC_{min} than the moderate braking condition (3.1 s and 7.8 s, respectively). ICC condition was not significant [$p<0.27$].
As in § 3.4.1, the analyses were repeated using only the first experimental block only, which turned the variable ICC condition into a between-subjects variable. The analysis of TTC_{gas}, $Dist_{br}$ yielded similar results as presented above. For TTC_{br}, there was a significant effect of ICC condition [$F(2,8)=4.5$, $p<0.05$]: TTC_{br} was larger for the condition without ICC than for the conditions with ICC, see Fig. 11. A post-hoc test revealed a significant difference between the no-ICC condition and both conditions with ICC [both $p<0.1$], but no difference between the ICCs types "on-gas" and "off-gas" [$p<0.7$]. For TTC_{min}, no effects were found (see Fig. 11).

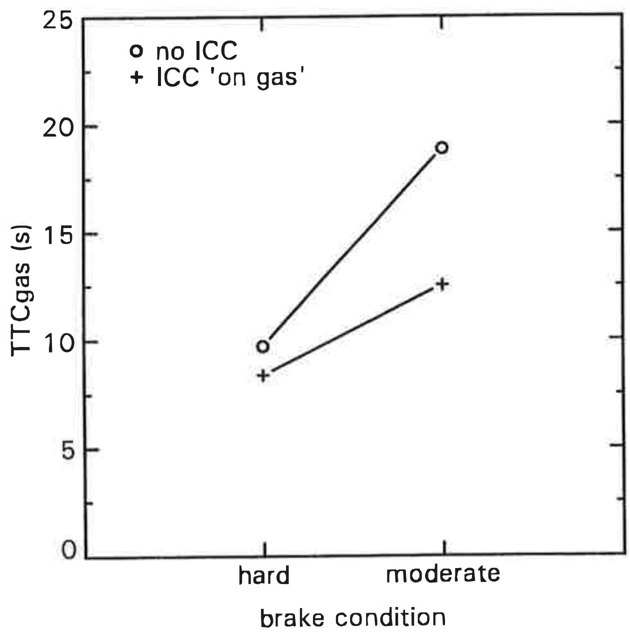

Fig. 10 TTC at the moment the gas pedal is first released as a function of ICC condition and of braking condition.

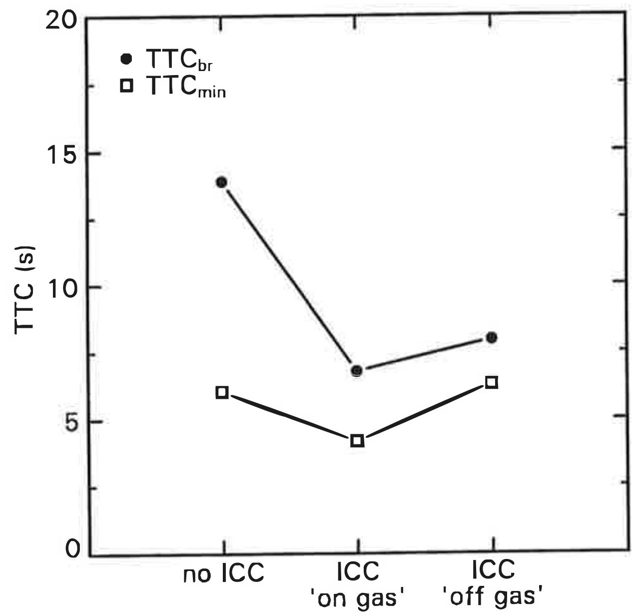

Fig. 11 TTC_{br} and TTC_{min} as a function of ICC condition (first block only).

To summarize these results:

- There was a trend showing that in terms of TTC, the gas pedal was released later in the ICC type "on-gas" condition compared to the condition without ICC.

- When only the first block of each subject is used in the analysis, there was an effect on TTC_{br} showing a later reaction for ICC (both types) compared to the condition without ICC; no differences between the ICC types were found.

3.6 Merge manoeuvres

During merge manoeuvres in ICC runs, subjects usually kept the cruise control activated (in 87% of the manoeuvres). The following distance during the merge manoeuvre was analysed using the same method as Hogema (1995), viz. by regarding four separate time instants:

D0 is the initial following distance, i.e. at the beginning of the scenario,

D1 is the following distance just before t_{merge} (i.e. the moment the lane-change was carried out),

D2 is the following distance just after t_{merge}, and

D3 is the following distance at the end of the scenario, i.e. just before the lead car started its lateral displacement to move to the hard shoulder.

These distances were determined for each manoeuvre separately. An ANOVA was carried out using the factors ICC condition and time moment (D0 to D3). There was only an effect of time instant [$F(2,30)=12$, $p<0.001$], see Fig. 12.

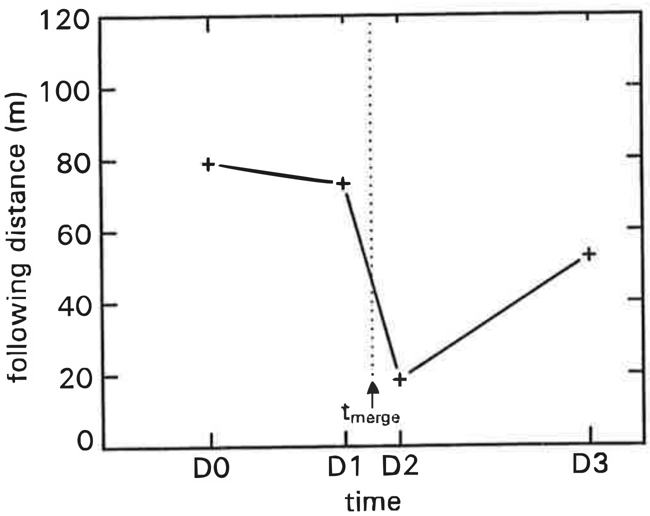

Fig. 12 Following distance during the merge scenario.

A post-hoc test showed that there was no significant difference between D0 and D1 [$p<0.6$]. From D1 to D2 there was a significant decrease, followed by a recovery from D2 to D3 [$p<0.001$ and $p<0.005$, respectively]. There was a trend showing that D3 remained somewhat below D0 and D1 [both $p<0.1$]. The latter may seem surprising: from an ICC system, one would expect a full recovery to the initial following distance.

An in-depth survey showed that there were responses with such characteristics, see Fig. 13 for an example. This figure shows that initially, there is a constant distance and speed. After the merge manoeuvre, the ICC distance controller detects too small a distance and responds

to this by commanding a negative acceleration. This yields a decrease of speed and an increase of following distance. Then the distance controller increases speed again in such a way that the final speed and distance are about equal to the initial values.
The results from the ANOVA showed that this pattern was not always present. This was caused by the speed subjects had set on the ICC. Often, this speed was equal to, or smaller than the lead car's speed. Consequently, the speed controller dominated the ICC instead of the distance controller, and therefore the initial distance (D0) was larger than would be expected based on the ICC's 1.5 s target headway. This can be seen in Fig. 12: the 80 m initial following distance corresponds to 2.6 s time headway. Given this initial situation, the merging lead car does not cause the ICC to regulate back to the initial distance D0.

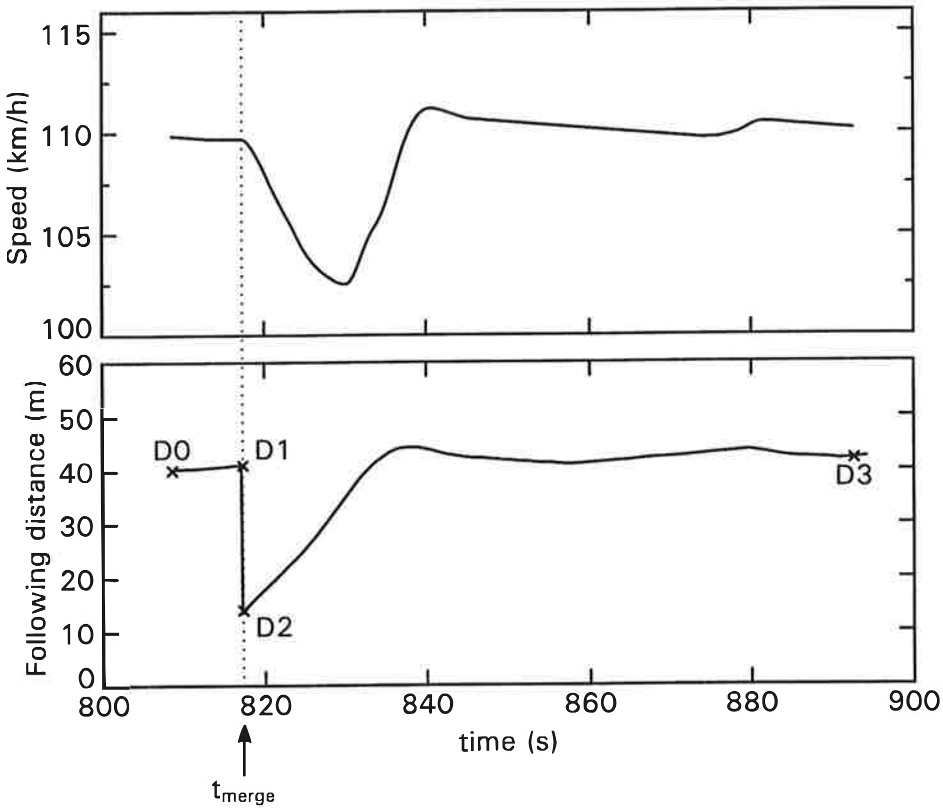

Fig. 13 Example of ICC response to the merging lead car (subject nr. 2, ICC type "off-gas", car-following run, merging lead car at t=817 s).

To investigate the correctness of this explanation, a further ANOVA was carried out, using only the ICC runs in which the subject had the ICC activated with a reference speed of at least 115 km/h. Averaged over both ICC types, the means were: D0=41.2 m, D1=41.7 m, D2=13.6 m, and D3=42.1 m. This clearly shows that for this sub-set, the final distance was equal to the initial distance.

3.7 Questionnaire results

Questionnaire results were analyzed both in a raw and a composite (factor-analytic) form, as described in § 2.5. The raw analysis gave the results of Table VI. Here the ratings given by subjects on the original 9 scales of the questionnaire have been averaged. Each scale ranges from −2 to +2, where higher scores indicate more favourable ratings.

Table VI Summary scores per original scale for ICCs "on gas" and "off gas".

ICC	On gas	Off gas	Sign. of difference
useful – senseless	1.25	1.50	ns
pleasant – unpleasant	0.33	1.25	0.05
good – bad	0.83	1.42	0.05
effective – superfluous	1.42	1.67	ns
nice – boring	0.50	0.92	ns
desirable – undesirable	0.67	1.00	ns
congenial – irritating	0.25	1.08	0.05
helpful – worthless	1.33	1.45	ns
alerting – sleep-provoking	−0.08	−0.25	ns

Only three of the original scales showed a significant difference in the ratings for ICCs "on gas" and "off gas", although the overall tendency was for the "off gas" ICC to yield consistently better ratings than the "on gas" ICC. Remarkably enough the average score on the "Alerting" scale showed an exception to the otherwise positive ratings for both types of ICC. The negative scores indicated that subjects suspected that an ICC, in whatever form, would generate a decreased level of alertness when being used.

Questionnaire ratings were also transformed to scores on the composite factors of "Perceived Usefulness" and "Perceived Comfort", as described in § 2.5. The composite scores, which can take values between −2 and +2, are shown in Fig. 14.
For both forms of ICC positive scores were obtained on both factors. However, t-tests showed that the ICC in which the foot could be taken off the gas pedal was judged both as more useful [t=2.73, df=11, p<0.05] and more comfortable [t=2.54, df=11, p<0.05] than the alternative.
The additional question which specifically asked about having to keep the foot on the gas pedal or not, confirmed the higher level of appreciation for the "off-gas" ICC type. After transforming ratings to values on the −2 to + 2 interval, the average scores turned out to be +1.67 for the "off-gas" type, versus −0.67 for the "on-gas" type.

The conclusion to be drawn from these subjective rating results is that they are highly in favour of the form of control where the driver's foot can rest on the floor while the ICC is engaged. Though the alternative solution was also judged to be above neutral on both the "Usefulness" and the "Comfort" dimension, the straightforward rating of the gas pedal MMI was remarkably negative.

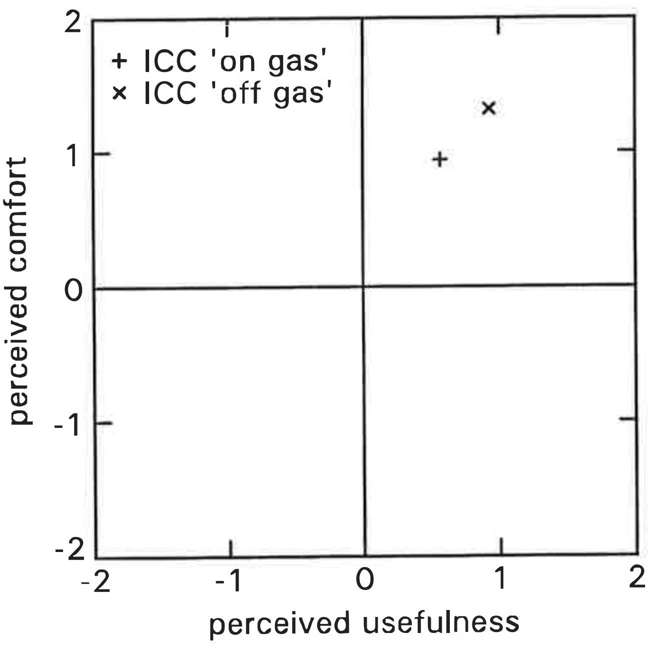

Fig. 14 Perceived "Usefulness" and perceived "Comfort" as a function of ICC type.

Degree of satisfaction with the modus operandi of the ICC

Average ratings of the degree of satisfaction with the relevant aspects of the ICC modus operandi were as follows (possible range: from −2 to +2):

Table VII Ratings of aspects of the ICC modus operandi.

Item	Mean	s.d.
Quality of speed control	+1.75	0.45
Quality of headway control	+1.58	0.51
Use of knobs and dials	+1.00	0.85
Quality of in-vehicle information display	+1.17	0.94

The degree of subject satisfaction is seen to vary from high to very high. If anything, the means by which the ICC control functions had to be executed could be scrutinized for possible improvements.

4 DISCUSSION AND CONCLUSIONS

Essentially, Intelligent Cruise Control takes over longitudinal vehicle control from the driver up to a certain level of deceleration. Therefore, ICC changes the role of the driver from actively controlling (in the loop) to monitoring the ICC's functioning (out of the loop). New driver tasks are the selection of ICC setpoints (in this study only the reference speed), and determining when to switch the ICC on and off. Especially the latter is important in critical situations where the ICC's maximum deceleration is not sufficient.

General effects of ICC

General expectations of ICC are that, compared with a human driver, longitudinal vehicle control is carried out with less variation. Such effects were found in this experiment: in car-following situations, ICC yields a reduction of the s.d. of speed, and a reduction of the proportion of short headways. This does not necessarily mean that the traffic performance is negatively affected: since headways longer than the ICC's target headway are reduced as well, there was no overall effect of ICC on the mean headway.
Similar findings were reported in the IRISS-1 study (Hogema, Van der Horst & Janssen, 1994), by Becker et al. (1994), and by Fancher et al. (1995). These effects are not due to changes in human driving behaviour, but they are the straightforward result of using a system that automatically controls speed and headway. A further in-depth analysis showed that with ICC, headways larger than the 1.5 s ICC target headway still occurred because of the ICC speed selected by the subject. When the ICC's reference speed is set at a speed that is equal to, or lower than the lead car's speed, the ICC's speed controller dominates the distance controller for headways larger than 1.5 s. Consequently, any headway larger than 1.5 s can result. This was also seen to influence the response in the scenario where a car merged between the subject and his initial lead car. The headway harmonisation which can be expected from ICC will only be realised to its full extent when the ICC's reference speed is set at a value larger than the lead car's speed.

With respect to speed choice, it was found that when driving with ICC, subjects selected a lower free-driving speed compared to the condition without ICC (effect size about 3–4 km/h). A similar effect was reported by Fancher et al. (1995): in a field study, subjects reported to (and in fact did) drive at a slightly higher mean velocity when controlling the vehicle themselves as compared to conventional or Intelligent Cruise Control.

The results also showed that subjects used the information displayed on the VMSs: at the start of the queue scenarios, they often disengaged the ICC based on a VMS message. This raises the question whether there are specific effects that can be attributed to the combination of ICC and VMS.

The most critical situations for ICC occur when the system's maximum deceleration level is insufficient, and consequently the driver must take over control. There were several of such scenarios in the experiment, viz. the stationary traffic queue (in free-driving and in car-following conditions) and the suddenly braking lead cars. These scenarios were all administered in two versions: a non-critical and a critical one (i.e. versions the ICC could, and could not deal with, respectively). In the free-driving approach to the traffic queue as well as in the braking lead cars scenario, there was an effect on TTC_{gas} showing that with the ICC type "on-gas", the gas pedal was released later compared to the condition without ICC. Additional effects were found on TTC_{br} and TTC_{min} when only the first experimental block

was included in the analysis, confirming the later reaction when driving with ICC (both types). This is in line with the findings of the IRISS-1 experiment (Hogema, Van der Horst & Janssen, 1994) where ICC was combined with an in-car information system. Since these effects were confirmed in the current study, they cannot be attributed entirely to the a distraction caused by the in-vehicle information of IRISS-1 being presented at the same time that a critical situation is developing.
The mean TTC_{min} values found in the most critical scenario (stationary traffic queue) were in the order of magnitude of 3.5 s without ICC, and 2.4 s with ICC (see Fig. 9). The size of this effect can be put in perspective by making a comparison with results from other studies. In a field experiment by Van der Horst (1990), where subjects approaching a stationary obstacle were instructed to brake as late as possible, a TTC_{min} of 1.1 s was found. Kaptein (1996) replicated this experiment in the TNO driving simulator while also extending the range of initial speeds. For comparison with the current results, the most relevant condition of his study is a high initial speed (90 or 120 km/h) and the hard braking instruction (this was "start braking at the latest moment you think you will still be able to reach standstill without colliding"). This yielded a mean TTC_{min} of approximately 1.8 s. Given the conditions under which this value was found (hard braking instruction, the same approach speed and the same driving simulator as in the current experiment), a TTC_{min} value of 1.8 s can be regarded as a suitable lower limit reference for the current study. With respect to this 1.8 s value, a change of TTC_{min} from 3.5 s to 2.4 s as caused by ICC is a considerable shift towards a minimum margin situation and is to be regarded a safety concern.

The effects of ICC condition on TTC measures were not present over the entire experiment, which shows that subjects apparently got used to the scenarios. This is also reflected in the high proportion of unnecessary ICC deactivations in the non-critical scenarios. After detecting the queue or the braking lead car, the typical reaction was to release the gas pedal and brake, regardless of the ICC condition and the actual urgency of the situation. Generally, a driver's brake reaction time will be shorter when he is expecting a situation that may require braking (Muto & Wierwille, 1982; Johansson & Rumar, 1971). This effect probably occurred in the current study. Nevertheless, the results do show that there are no adverse effects of ICC as long as the driver is sufficiently prepared to take over control. When the frequency of the emergency-like scenarios is reduced, less favourable results may be found. This is illustrated by a driving simulator experiment by Nilsson (1995), where subjects were only confronted once with a stationary traffic queue; another difference is that the ICC used in that experiment did not respond to stationary obstacles (in correspondence with the functioning of many ICC prototypes). The results of Nilsson's study showed that with ICC, more "collisions" occurred.

The subjective ratings of ICC were generally positive. As in the previous experiment (Hogema, Van der Horst & Janssen, 1994), only the average score on the "Alertness" scale showed an exception to the overall positive ratings. Subjects suspected that using ICC might generate a decreased level of alertness. However, this does not necessarily mean that such an effect would really occur. Furthermore, if this effect does occur, drivers might be able to compensate for it, for instance by not using the ICC in those situations. Therefore, a total effect on safety cannot be predicted based on the questionnaire results.

ICC type "on-gas" vs. "off-gas"

The subjective results clearly confirmed the expectations from IRISS-1 (Hogema, Van der Horst & Janssen, 1994): drivers strongly prefer the ICC type "off-gas" compared to the "on-gas" type. There was a minor difference in ICC usage: ICC type "on-gas" was deactivated more frequently than ICC type "off-gas". Otherwise, no differences were found in driving behaviour between the two ICC types (neither in critical nor in non-critical situations). However, when the frequency of emergency-like events is reduced, an effect of ICC as such is more likely to occur (Nilsson, 1995), and possibly a difference between the two ICC types as well. Based on the results of this study, there is no reason to prefer ICC systems which requires to keep the foot on the gas pedal.

MIXIC

This experiment yielded several results with relevance for the MIXIC Driver Model as described by Van Arem, Hogema, and Verheul (1995). First, ICC yielded a reduction of the free-driving speed. Such an effect is currently not included in the MIXIC Driver Model.
The current MIXIC Driver Model takes over control from the ICC when the ICC has reached its maximum deceleration level *and* simultaneously the driver would decelerate stronger if he was driving himself. This is not in line with the results of the current study, which showed that when the ICC is switched off in a critical situation, this usually occurs before the ICC has reached its maximum deceleration level.
With respect to (re-)activation of ICC, subjects showed a preference to activate ICC when the lead car's speed exceeded the subject's speed, i.e. when there is no collision course. Additionally, it seems that subjects avoided activating the ICC at relatively small headways. These findings can be used for several adjustments of the MIXIC Driver Model.

From this study, the following issues for further research emerged.
- The optimal settings of ICC controller parameters (especially the ICC's target headway) in relation to driver acceptance and driver behaviour is unknown. The current setpoint of 1.5 s is rather conservative for today's traffic (Van der Horst, 1993). The traffic condition should be considered in this context as well. Possibly, the current conservative setpoint of 1.5 s is not very suitable for dense traffic conditions.
- It was found that the harmonizing effect of ICC on speed and headway distributions could be improved by an adequate selection of the ICC target speed. This could be accomplished automatically by using a roadside-to-vehicle communication system (as studied in the previous ICC experiment of Hogema, Van der Horst & Janssen, 1994). This also brings back the issue of in-vehicle information presentation in relation to road-side information, and of possible compensating effects.
- In addition to this, the specific effects of VMS on driving behaviour with and without ICC, respectively, seem worthwhile to investigate in further detail.
- To explore the effects of expectancy of critical situations on the driver's reaction, the frequency of occurrence of these critical events could be varied.
- So far, the IRISS-1 and IRISS-2 projects dealt with fixed-base driving simulator studies to explore several forms of ICC. To validate the results of these studies in a more absolute manner (instead of relative validity as frequently obtained in driving simulator

studies, see Kaptein et al., 1995), a road study on the most promising form of ICC (the foot-off-gas type) with the instrumented vehicle ICACAD of the TNO-HFRI is considered worthwhile.

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Soesterberg, 15 February 1996

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 automatic accelerating and braking.

A block diagram of the entire system as implemented in the TNO driving simulator is given in Fig. A.1; its components will be explained below. Text in italic refers to block or signal names in Fig. A.1.

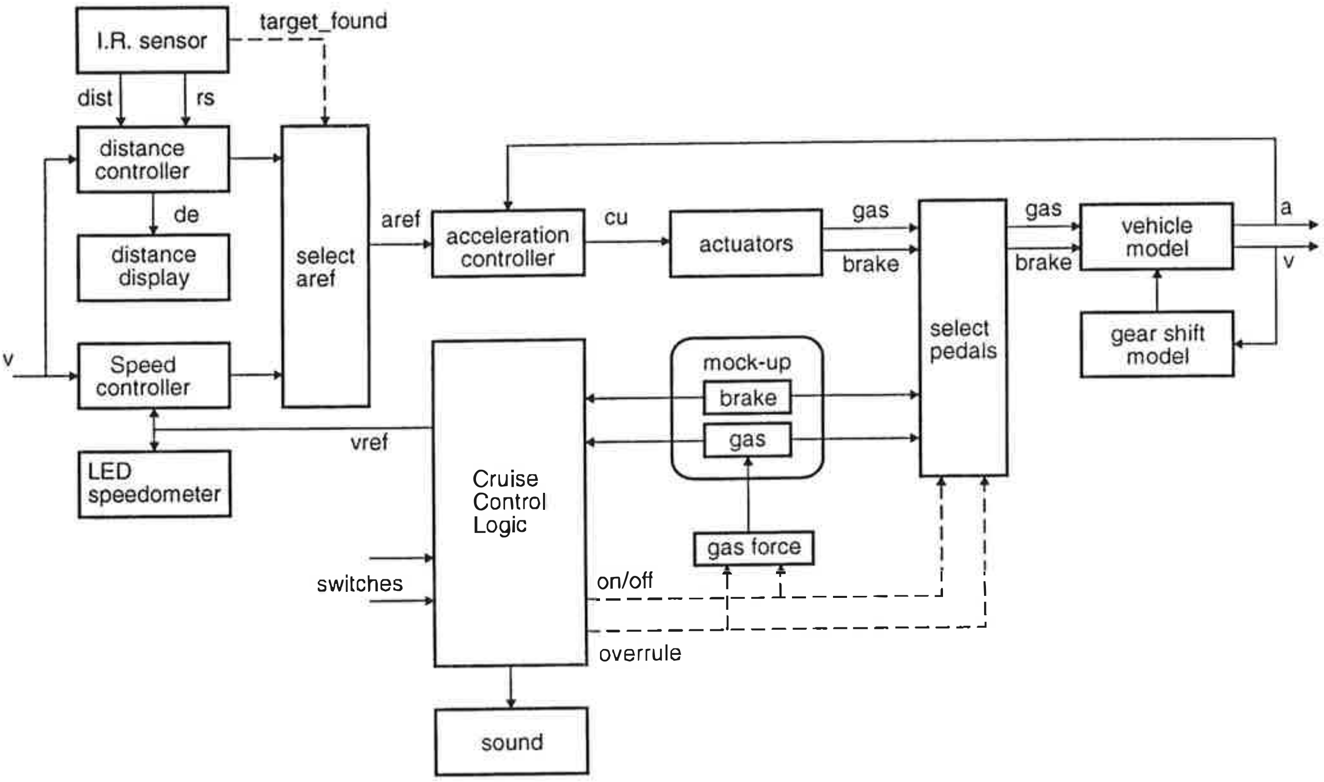

Fig. A.1 Block diagram of the ICC system.

The *vehicle model* was the same model used in other experiments in the driving simulator. At a frequency of 90 Hz, it calculated among other things the momentaneous position and heading (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 calculated an appropriate gear ratio.

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

When the ICC is on, it calculated an acceleration reference *aref*. An inner control loop had the objective of realizing this desired acceleration as well as possible. The *acceleration controller* compared aref which the actual acceleration *a*, and calculated the controller output *cu*. This acceleration controller was of the PI type with anti-reset wind-up. Next, the *actuators* determined appropriate gas and brake signals from cu.

The signal aref was taken from either the *distance controller* output *aref_d* or the *speed controller* output *aref_v*. When a lead vehicle was detected, indicated by the variable *target_found*, aref equalled the most restrictive of aref_d and aref_v. When no lead car was present, the ICC was in speed control mode and then aref equalled aref_v.

The *IR sensor* produced the distance *dist* and relative speed *rs* to a lead vehicle when a lead car was within the sensor's range of 120 m. In the simulator an ideal sensor was realized in the sense that it had no delay or measurement noise. Additionally, it always correctly detected a lead car in the driver's lane when this lead car was within the sensor range, even when it was stationary. In reality, the sensor beam might see past a lead car for example in a sharp curve, and in many prototype ICCs, stationary obstacles are not reacted to.

The *distance controller* produced aref_d based on the relative speed *rs* and on *de*, the internally calculated distance error (i.e. the deviation in % of the actual distance from the reference distance). The reference distance was a linear function of the speed *v* and corresponded to a constant time headway of 1.5 s:

$$D_{ref} = v * \tau$$

where

D_{ref} is the reference distance in m,
v is the current speed of the ICC vehicle in m/s, and
τ is the ICC's target headway in s, set at 1.5 s.

The values for *de* and *rs* were used as indices in a two-dimensional look-up table to obtain aref_d. This table, which was developed using fuzzy control methods, was made available for the IRISS studies by Daimler-Benz.
The value of *de* also determined which of the five LEDs on the bar of the *distance display* were switched on. Green lights indicated a distance larger than the reference distance and red lights meant too small a distance (see Table A.I).

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

L1 red	L2 red	L3 yellow	L4 green	L5 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 *speed controller* was a simple P-type controller: its output was proportional to the difference between the actual speed *v* and the setpoint *vref*.

The speed controller and distance controller outputs were limited within the boundaries shown in Table A.II.

Table A.II Limits of the 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 Logic* kept track of the state of the ICC, i.e. whether it was on, off, or overruled, and of the reference speed *vref*. The ICC state was determined by the driver by means of the *switches* and by the gas or brake pedal position of the mock-up. The switches allowed the driver to switch the ICC on or off, and to adjust the reference speed (see § 2.2). The reference speed was shown by a LED on the speedometer.

In accordance with the Daimler-Benz approach, two additional *sounds* were implemented to inform the driver about the state (transitions) of the ICC. The first was a simple beep when the ICC is disengaged. The second was an alarm signal that was heard when the ICC detected a lead car driving so slowly that the maximum deceleration is not sufficient to avoid a collision, given the momentaneous distance and relative speed. The criterion used was:

$$D < \frac{v_{dif}^2}{2a}$$

where

D is the momentaneous following distance (m),
v_{dif} is the speed difference (m/s),
and a is the ICC's maximum deceleration (m/s²).

When using for *a* the value of (−)1.8 m/s² from Table A.II, the warning became too precautious in practice. Therefore, a value of 3.5 m/s² was used instead.

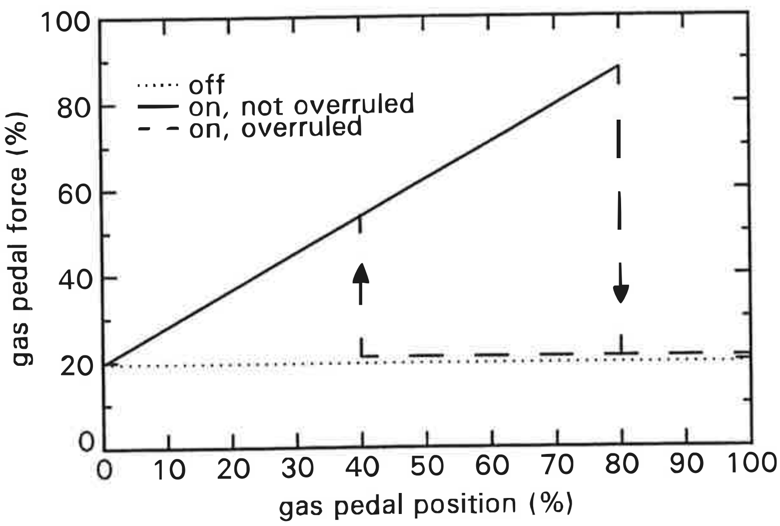

Fig. A.2 Force-position characteristic of the gas pedal.

The type "on-gas" ICC required the driver to keep his foot on the gas pedal while ICC was active. In order to make it clear to the driver whether this ICC type was 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 was produced by a servo motor. The state-dependent characteristic is shown in Fig. A.2. As long as the ICC was off, the force was constant at about 20% (where 100% corresponds to 185 N, the maximum force the servo motor cold deliver). When the driver switched the ICC on, this was felt as an increasing force when the gas pedal position was increased. As long as the pedal position remained between 0 and 80% the ICC stayed on. The type "on-gas" ICC could be overruled by pressing the pedal position above 80%. Then the force dropped to a lower, constant level. Because of a hysteresis in the characteristic, the driver now had the pedal range of 40 to 100% to override the system. Only when the position was lowered beneath 40% the system was no longer overruled, which was felt as an sudden increase of the pedal force.

When the driver engaged the ICC while the gas pedal position exceeded 80%, it was 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.

The type "off-gas" ICC allowed the driver to keep his foot off the gas pedal when ICC was active (as in the Daimler-Benz prototype). This ICC was automatically switched off as soon as the driver pressed the brake pedal. The driver could always overrule an ICC of this type by pressing the gas pedal deeper than the gas actuator position as determined by the ICC algorithm.

APPENDIX B DETAILED DESCRIPTION OF THE SCENARIOS

Fig. B.1 illustrates the ICC conditions and the traffic conditions (free driving/car following). There were three blocks, corresponding to the three ICC conditions: ICC type "on-gas", ICC type "off-gas", and no ICC. The order of these ICC conditions was balanced over subjects. Furthermore, each block consisted of two runs: a free-driving and a car-following run (order balanced over subjects).

ICC 1		ICC 2		NO ICC		ICC condition
free	fol.	free	fol.	free	fol.	traffic condition

Fig. B.1 ICC and traffic conditions condition.

Within each run, there were five standard "120 km/h" sections and (in random order) the four scenarios 1, 2, 3, and 4 (see Fig. B.2).

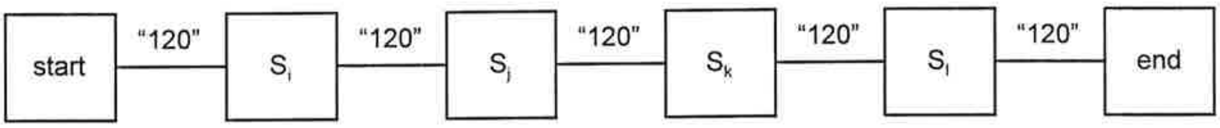

Fig. B.2 Sequence of scenarios within each run.

The contents of the scenarios were as follows:

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

2 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 following condition, the lead cars started to decelerate (with 1 m/s^2) just after passing the first "80" sign until they reached a speed of 80 km/h.

3 In the "stationary 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.
When approaching the queue in the car-following condition, the platoon leader started to decelerate moderately (1 m/s^2) when he passed the first VMS indicating 50 km/h. He maintained this deceleration for 5.2 s, resulting in a speed of 28 m/s at the moment his distance to the queue was 130 m. Then he increased his deceleration to strong braking (3 m/s^2), which was maintained for another 9.4 s. This was just sufficient to come to a

stop behind the queue without colliding. The moment for switching from moderate to strong deceleration was determined using data from Kaptein (1995), who studied braking behaviour in a simulator experiment.

The other cars in the platoon used the same deceleration pattern as a function of time. Each car's braking was initiated a certain reaction time after its lead car started braking, such that the braking was started 10 m before the position where its lead car started braking. In this way, the platoon ultimately reached standstill with 10 m distance between each vehicle (corresponding to a 4.60 m bumper to bumper distance). During this process, the subject was confronted with a lead car braking at 3 m/s² for a while, and consequently the subject had to take over control.

After the subject had lowered his speed below 15 km/h, the queue accelerated (with 1 m/s²) to 50 km/h, and after a while moved to the hard shoulder. In the car-following condition, the original lead cars remained on the road. The second VMS after that point would indicate the end of the speed limit, which ended the queue scenario.

4 The "moving traffic queue" scenario started the same as the stationary version: 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.

In the free-driving condition, the queue started to accelerate (2 m/s²) at the moment the distance of the subject to the queue became smaller than 330 m. This acceleration continued until the queue reached a speed of 50 km/h, which was always before the queue came within the ICC sensor range. When the distance of the subject to the queue became smaller than 100 m, the queue accelerated further (1 m/s²) until they reached a speed of 75 km/h.

In the car-following condition, the platoon leader started to decelerate with 1 m/s² at the moment he passed the first "50" sign, and continued this braking until he reached a speed of 50 km/h. Meanwhile, the queue started to accelerate when the distance of the platoon leader to the queue became smaller than 187 m. The queue accelerated with 2 m/s² until they reached a speed of 50 km/h and then maintained a constant speed. At this time, the platoon leader had reached a time headway of 1 s with respect to the last car in the queue, and he started following the moving queue. Each subsequent car in the platoon approaching the queue used the same acceleration pattern as a function of time. For each car, the deceleration was initiated a reaction time after the lead car started braking. This reaction time was selected equal the initial time headway.

Then the subject drove behind a platoon driving at either 50 km/h or 75 km/h. After a while, the cars that initially were in the queue moved to the hard shoulder. In the car-following condition, the original lead cars remained on the road. The second VMS after that point would indicate the end of the speed limit, which ended the queue scenario.

In the car-following condition during the standard scenario, the following scenario's occurred once in each run (in random order):

5 The sudden hard braking manoeuvre of the lead cars consisted of a deceleration at 3 m/s² lasting for 8 s, initiated by each car at the same time. If the driver would not take over control from the ICC, a collision occurred with a speed difference of 41 km/h and the

alarm was sounded during the last 1.3 s before the collision. After the braking manoeuvre, the other cars maintained their new speed for 15 s, and then accelerated to 120 km/h.

6 The sudden moderate braking manoeuvres of the lead cars consisted of a deceleration at 1.5 m/s^2 lasting for 8 s, initiated by each car at the same time. This did not cause an urgent situation: with ICC active, the minimum TTC over the entire manoeuvre was 13 s; the alarm was not sounded and the driver did not have to take over control from the ICC. After the braking manoeuvre, the other cars maintained their new speed for 15 s, and then accelerated to 120 km/h.

7 a car in the left lane appeared, overtook the subject and then merged between the subject and his initial lead car, such that the subject's following distance was suddenly reduced, bit there was no change in speed difference. This car stayed there for 2 km and then moved to hard shoulder and braked until it had fully stopped.

In the free-driving condition, the following scenario occurred in three out of the five standard scenario's (selected at random):

8 single lead car appeared, overtaking the subject with a speed that was 18 km/h (5 m/s) higher than the subject's mean speed over the last 10 s. When this car reached a position 100 m ahead of the subject, it executed a lane-change manoeuvre to the right lane which took 6 s, and then decelerated to a speed of 10 km/h below the subject's free-driving speed. This created an approach course, and the subject could either overtake this car or follow it. This car stayed on the road for 2 km and then moved to hard shoulder and braked until it had fully stopped.

Instruction and training runs

Before each ICC block, the subject was first given an instruction run and a training run. These took place on the same road environment as used in the experimental run, however, without any of the scenarios occurring. Instead, there would be single lead cars on the right lane, about 400 m apart, whose speed fluctuated between 80 and 90 km/h. The subject could either overtake these cars or follow them to get acquainted with the car-following function of the ICC.

APPENDIX C QUESTIONNAIRES ON SUBJECTIVE JUDGMENT

On the following pages, the questionnaires used in the experiment are given.

IRISS-2 INTELLIGENT CRUISE CONTROL SIMULATOR-EXPERIMENT

ICC-conditie 1 (voet-op-gas)

Naam: ______________________ Datum: ______________________

Proefpersoon nummer: __________ Proefleider: ______________________

Zojuist heeft U rondgereden met een systeem voor "Cruise Control". Zou U hieronder willen aangeven wat U van het systeem vond tijdens het rijden?

Er zijn telkens vijf antwoordmogelijkheden. Als U een term perfect van toepassing vindt, zet dan een kruisje in het vakje dat het dichtst bij die term staat. Als U een term in zekere mate van toepassing vindt zet dan aan die kant, dus links of rechts van het middelste vakje, een kruisje. Als U er geen uitgesproken mening over hebt, zet dan een kruisje in het midden.

Ik vond het Cruise Control systeem tijdens het rijden:

nuttig						zinloos
plezierig						onplezierig
goed						slecht
effectief						onnodig
leuk						vervelend
gewenst						ongewenst
aangenaam						irritant
behulpzaam						waardeloos
waakzaamheidverhogend						slaapverwekkend

U moest de voet op het gas houden om de cruise control ingeschakeld te houden. Wat is Uw oordeel daarover?

positief						negatief

IRISS-2 INTELLIGENT CRUISE CONTROL SIMULATOR-EXPERIMENT

ICC-conditie 2 (voet-van-gas)

Naam: ______________________________ Datum: ________________________

Proefpersoon nummer: ____________ Proefleider: ________________________

Zojuist heeft U rondgereden met een systeem voor "Cruise Control". Zou U hieronder willen aangeven wat U van het systeem vond tijdens het rijden?

Er zijn telkens vijf antwoordmogelijkheden. Als U een term perfect van toepassing vindt, zet dan een kruisje in het vakje dat het dichtst bij die term staat. Als U een term in zekere mate van toepassing vindt zet dan aan die kant, dus links of rechts van het middelste vakje, een kruisje. Als U er geen uitgesproken mening over hebt, zet dan een kruisje in het midden.

Ik vond het Cruise Control systeem tijdens het rijden:

nuttig						zinloos
plezierig						onplezierig
goed						slecht
effectief						onnodig
leuk						vervelend
gewenst						ongewenst
aangenaam						irritant
behulpzaam						waardeloos
waakzaamheidverhogend						slaapverwekkend

U kon de voet van het gas nemen terwijl het cruise control ingeschakeld bleef. Wat is Uw oordeel daarover?

positief						negatief

J.H. Hogema, 6 oktober 1995

IRISS-2 INTELLIGENT CRUISE CONTROL SIMULATOR-EXPERIMENT

EIND-VRAGENLIJST

Naam: ____________________ Datum: ____________________

Proefpersoon nummer: __________ Proefleider: ____________________

Hier volgen nog enkele nadere vragen over wat U van het systeem vond. Ook hier zijn telkens vijf antwoordmogelijkheden.
Onder iedere vraag is ruimte opengelaten waar U verdere opmerkingen kwijt kunt.

(1) Wat vond U van de manier waarop het systeem de rijsnelheid regelde?

slecht						goed

(2) Wat vond U van de manier waarop het systeem de afstand tot de voorligger regelde?

slecht						goed

(3) Wat vond U van de manier waarop U het systeem moest instellen en bedienen, dus van de knoppen en schakelaars?

slecht						goed

(4) Wat vond U van de manier waarop U van het systeem kon aflezen wat de ingestelde snelheid was en de indicatie van de afstand tot de voorligger?

slecht						goed