The impact of Autonomous Intelligent Cruise Control on traffic flow

Bart van Arem
TNO Institute for Infrastructure, Transport and Regional Development
P.O. Box 6041, 2600 JA Delft, The Netherlands

Jeroen H. Hogema
TNO Human Factors Research Institute
Soesterberg, The Netherlands

Stef A. Smulders
Ministry of Transport, Public Works & Water Management, Transport Research Centre
Rotterdam, The Netherlands

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ABSTRACT

Autonomous Intelligent Cruise Control (AICC) is a system in a road-vehicle that automatically maintains a specified speed, taking into account a minimal distance (target headway) with respect to predecessors. The objective of the work reported here was to gain an insight into the effects of the introduction of AICC on the traffic performance and safety on motorways.

Simulation experiments were conducted for motorway traffic with varying conditions for the level of AICC penetration, the AICC target headway setting, traffic flow levels and traffic compositions. The study has confirmed the notion from earlier studies that AICC systems can contribute to a more stable traffic flow without sacrificing capacity. However, a deterioration on the traffic performance was found in some cases at the higher levels of traffic demand.

INTRODUCTION

Automated vehicle guidance (AVG) is regarded as a promising application of technology to improve road network traffic performance and safety. AVG systems partly or entirely take over the driving tasks (lane and distance keeping, manoeuvring) of a driver. Such systems may involve communication with road-side systems and/or other vehicles.

Autonomous Intelligent Cruise Control (AICC) is regarded as one of the first practically feasible AVG systems. AICC is a system that automatically maintains a specified speed, taking into account a minimal distance (target headway) with respect to predecessors. AICC is an autonomous system: it does not communicate with other vehicles or road-side systems. Therefore, AICC is applicable in mixed traffic flows: vehicles with and without AICC can use the same road.

The objective of the work reported here was to gain an insight into the effects of the introduction of AICC on the traffic performance and safety on motorways. The AICC systems are assumed to have a limited acceleration and deceleration range: a driver can switch the AICC system on and off. In emergency braking situations where the AICC deceleration is too small to avoid a collision, the driver has to overrule the AICC. The impacts were assessed using as input real traffic measurements for different levels of traffic.

This paper will focus on the most important results that were obtained. Readers that are interested in the details of the study are referred to the project reports (Van Arem et al, 1995,1995b). The paper is organized as follows. In Section 2 a review will be given of results from the literature on the impact assessment of AICC by traffic simulation. Section 3 will give a short description of the microscopic traffic simulation model MIXIC that was used for the analyses. Section 4 will focus on the experimental setup, after which Section 5 will give the highlights of the results. Finally, Section 6 will give conclusions.

RESULTS FROM THE LITERATURE

In Zhang (1991) some first results are given using the Autobahn Simulator model. Both a two lane and three lane motorway are considered while varying the level of penetration of AICC between 0%, 30%, 50% and 100%. The paper concludes that AICC improves safety, while the macroscopic characteristics of the traffic flow remain almost unchanged.
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In Broqua et al. (1991) a two lane motorway stretch of 6 km is considered. Results are presented for 20% and 40% level of AICC penetration and an AICC target headway of 1 s and 2 s. Overall it is concluded that even with a safety related choice of the AICC parameters, a significant improvement in efficiency can be obtained.

Mauro (1992) uses the same AICC design, while focusing on a target headway of 1.5 s. One of the indicators given is the motorway reliability. The motorway reliability of a traffic situation is the probability that the situation does not produce a traffic breakdown within a finite time. Mauro (1992) argues how AICC could increase the motorway reliability. An example is given of a case in which a fixed traffic demand near to saturation (in this case, at a level of 3200 veh/h for a two-lane motorway) produces a severe traffic breakdown. In the same situation with 40% AICC vehicles, this breakdown does not occur. It is argued further that by increasing motorway reliability, AICC can also reduce the average journey time.

In Morello et al. (1994), the same AICC design is assumed (1.5 s), and a maximal deceleration of $-2.5 \text{ ms}^{-2}$ is imposed. Thus, the AICC serves as a comfort device, it is not intended for emergency braking. At a 100% penetration rate of AICC, the number of critical situations is reduced by 80%, see also Benz (1994). Evidently, the number of short headways decreases. The decelerations are less severe. There is a clear shift in the distribution toward the high Time-to-collisions.

Concluding, available results indicate that for German and Italian motorway situations safety is increased without sacrificing efficiency. The traffic volumes considered however, appear to be somewhat lower than volumes close to saturation on Dutch motorways. With respect to safety the conclusions are quite intuitive, with limited quantitative foundation.

The analyses may be improved in several aspects. First, the interaction between driver, vehicle and AICC functions may be modelled more explicitly. Next, the relation between AICC and motorway reliability can be addressed more explicitly, e.g., by studying shockwaves. Finally, situations have to be considered with traffic volumes close to saturation, e.g., by using real traffic measurement as input to the simulations.

THE MICROSCOPIC TRAFFIC SIMULATION MODEL MIXIC

MIXIC simulates traffic on a link level in a network. Given an input of traffic flow, it simulates the traffic behaviour on this link and produces traffic statistics. The type of road network studied in MIXIC is a sequence of homogeneous motorway links, without on- or off-ramps, and with all links having the same number of lanes. As input MIXIC uses real traffic measurements (time instant, lane, speed and length). New positions and states are calculated in each time step (set to 0.1 s) by a driver and vehicle model. In each iteration, the driver model produces the driver actions, consisting of the lane change action and the new pedal and gear positions. The AICC may take over certain actions from the driver. Next, the vehicle model calculates the resulting acceleration of the vehicle.

The driver model consists of three main components. The first two describe the actual driving behaviour: these are the lane-change model and the longitudinal driver model. In each simulation time step, these sub-models are executed to produce the lane-change decision and the driver's actions on the vehicle controls, respectively. For vehicles that are equipped with AICC, the third component models the interaction between the driver and the AICC; this part indicates when the AICC is switched on and off.
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The vehicle model describes the dynamic behaviour as a result of the interaction with the driver and the road, taking into account the ambient conditions. The input variables from the driver model are the position of the accelerator pedal and the force applied on the brake pedal. The vehicle model uses information on the characteristics of the vehicle, the road geometry, the condition of the road and the wind. The output of the vehicle model is an updated vehicle acceleration, which is used to calculate a new vehicle speed and position. The vehicle model calculates the vehicle acceleration based on the vehicle inertia and the resultant force of driving resistant forces, traction forces and braking forces.

An AICC system is capable of automatically regulating a vehicle’s speed and following distance when following another vehicle. To obtain the information needed for this control task, a radar-like sensor is used. The core of the AICC consists of a control algorithm, which influences the vehicle by means of a gas and brake actuator. In MLXIC the AICC reference headway is defined by:

\[ hw_{\text{ref}} = M_{\text{aicc}} + v \times \tau_{\text{aicc}} \]  (3.1)

where

- \( v \) = current speed (m/s)
- \( M_{\text{aicc}} \) = a constant offset, or safety margin (m)
- \( \tau_{\text{aicc}} \) = time-headway setting (s)

EXPERIMENTAL SETUP

The data used were collected on the A2 motorway between Utrecht and Amsterdam. The measurements were collected via the research facility of the Motorway Control Signalling System. The measurements consist of arrival instant, lane, speed and length of passing vehicles at 3 cross-sections. The motorway comprises three lanes. The speed limit is 120 km/h. In the Netherlands vehicles drive on the right side of the road. Of the available data, 4 peaks were selected, each comprising three hours of traffic during dry weather and normal visibility. Table 4.1 gives basic characteristics for each peak.

**Table 4.1 Traffic characteristics peak in percentages**

<table>
<thead>
<tr>
<th></th>
<th>peak 1</th>
<th>peak 2</th>
<th>peak 3</th>
<th>peak 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>traffic volume (veh/h)</td>
<td>4600</td>
<td>3965</td>
<td>5520</td>
<td>5950</td>
</tr>
<tr>
<td>passenger cars (%)</td>
<td>86</td>
<td>92</td>
<td>91</td>
<td>95</td>
</tr>
<tr>
<td>vans (%)</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>trucks (%)</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

In order to investigate traffic performance, the speed-flow and speed-density diagram were studied. Further, average and standard deviation of the travel time and the speed were analyzed. To investigate traffic safety, the indicators selected addressed shockwaves, Time-to-collisions and headways. Shock waves were
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identified by tracing individual vehicles. The following criteria were used as the defining elements of a shock wave. Each occurrence of a vehicle with a deceleration stronger than $-5 \text{ m/s}^2$ indicates a possible involvement in a shockwave. Occurrences are assigned to the same shockwave if they occur within a certain time (3 s) and space (50 m). A candidate shockwave is considered to be a genuine shockwave if at least 3 vehicles are involved.

The experiments addressed varying conditions for the level of AICC penetration in passenger cars (0%, 20%, 40%), the AICC target headway setting at 100 km/h (1.0 s, 1.5 s) and peaks and locations (reflecting different traffic flow levels and traffic compositions).

The simulations were conducted for three consecutive three lane motorway sections of 1 km of length each. The middle stretch (1000-2000 m from the start) was used to conduct measurements. The cross-section measurements were conducted at 1500 m. A calibration of the simulation results without AICC took place first (Van Arem et al., 1995a).

RESULTS

Inspection of the simulation results revealed that all 4 peaks could all be simulated without any sign of congestion, except for the case of a combination of a high traffic demand and 40% AICC with a target headway of 1.5 s, see Figure 5.1 and 5.2.

The collapse in speed on the left lane did not take place for the other cases considered for peak 3. To some extent it also occurred for peak 4, which might appear surprising since the traffic volume in peak 4 is larger than in peak 3. This is probably due to the amount of clustering within the peaks. In the less dense peaks a decrease in speed was found, but not as large as in Figure 5.2.

In Figure 5.2 the large speed differences between the speeds on the different lanes appear to be unrealistic. In normal traffic situations such speed differences are unlikely. The traffic on the middle lane does not break down. In reality, drivers will decelerate in such situations. In MIXIC both the longitudinal driver model and the AICC only take into account vehicles in the same lane. The amount of traffic carried
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on the left lane showed an increase for the situation with AICC compared with the situation without AICC. The AICC vehicles drive on the left lane more than other drivers. A possible explanation can be found in the rules according to which a driver changes to the right: one of the conditions for wanting to change to the right is that the vehicle has reached, or nearly reached, the intended speed or the vehicle has (nearly) reached the maximum comfortable acceleration. Clearly, this rule is not satisfied in following situations.

Figures 5.3 and 5.4 plot the measured speeds and traffic volumes per 5 minutes for peak 4 with 40% AICC with target headway 1.0 and 1.5 s.

![Figure 5.3 Speed volume relation peak 4, 40% AICC (1.0)](image)

![Figure 5.4 Speed volume relation peak 4, 40% AICC (1.5)](image)

Again, it is apparent that the traffic flow suffers from 40% AICC with target headway 1.5. This does not happen for AICC with a target headway of 1.0 s.

In order to obtain quantitative results which can confirm the qualitative results described in the preceding, a number of statistical tests was conducted. The tests were carried out using a significance level of 0.1 (T-value at 1.30). For each peak the case of no AICC was tested against the alternatives with AICC.

Table 5.1 gives a summary of the results for peak 3. Numbers which differ significantly from the case with no AICC are marked by (x).

<table>
<thead>
<tr>
<th>Table 5.1</th>
<th>Testing results traffic performance peak 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>no AICC</td>
</tr>
<tr>
<td>Average travel time (s)</td>
<td>33.46</td>
</tr>
<tr>
<td>Stand. dev. travel time (s)</td>
<td>3.70</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>109.51</td>
</tr>
<tr>
<td>Stand. dev. speed (km/h)</td>
<td>11.26</td>
</tr>
</tbody>
</table>
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The average travel time increases significantly in all cases with AIICC. The increase is quite small except for the case 40% AIICC (1.5). The standard deviation of the travel time decreases, for most cases significantly, except the 1.5 s target headway cases for peak 3.

Both the average and the standard deviation of the speed decrease. However, for the situation 40% AIICC (1.5) the standard deviation of the speed increases. This is due to a collapsing speed on the left lane. This collapsing speed gives a large standard deviation of the speed in a number of time intervals (the standard deviation is computed over all lanes and the medium and right lane did not 'collapse').

Concerning the shockwaves, both the number of shockwaves and the number of vehicles per shockwave decreases in almost all cases. However, this is seldom significant, see Table 5.3, probably due to a large standard deviation of the number of shockwaves per 5 minute. The fact that the decrease was found in almost all cases may however be considered as some evidence for the statement that the decrease is true in a general sense.

Table 5.3 Testing results for shockwaves in peak 1

<table>
<thead>
<tr>
<th>Quantity</th>
<th>no AIICC</th>
<th>20% AIICC (1.0)</th>
<th>20% AIICC (1.5)</th>
<th>40% AIICC (1.0)</th>
<th>40% AIICC (1.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average nr. shockwaves/5 min</td>
<td>0.28</td>
<td>0.14</td>
<td>0.11</td>
<td>0.20</td>
<td>0.06 (x)</td>
</tr>
<tr>
<td>Average nr. of vehicles per</td>
<td>4.6</td>
<td>4.8</td>
<td>4.3</td>
<td>4.7</td>
<td>5.0</td>
</tr>
<tr>
<td>shockwave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The distributions of the headways and TTCs give an indication for the traffic safety or risk. For the TTCs an overall increasing tendency was found. As the TTCs showed an overall increase, the fraction of TTCs below 4 s showed a decrease, which appeared to occur on all lanes. However, in the cases of a high traffic demand and a target headway of 1.5 s, the percentage of TTCs < 4 s decreases on the right lane but remains equal or even increases on the middle and left lane.

For passenger cars without AIICC it appeared that headways tend to become smaller as AIICC is introduced. For the situation of 40% AIICC with a target headway of 1.5 s this is the most prominent (an increase from 76% to 87% in headways less than 2 s). For AIICC vehicles the headways tend to be larger than for normal vehicles. This is logical, since the reference headway of AIICC vehicles is larger than for human drivers. Therefore, if the division over the lanes would remain unchanged, then the increase of headways for AIICC vehicles automatically implies a decrease of the headways for vehicles without AIICC.

CONCLUSIONS

With respect to traffic performance, the results found in the present study are not in total agreement with earlier results from the literature. In particular the result that for Italian and German motorways AIICC with a 1.5 s target headway increases safety without sacrificing capacity has not been reproduced. There are strong indications that a penetration of 40% AIICC with a 1.5 s target headway on passenger cars.
The impact of Autonomous Intelligent Cruise Control on traffic flow decreases motorway capacity. It has to be noted that the results in the present study were obtained with both moderate and heavy traffic loads. AICC tends to increase the travel time slightly (this was found by Zhang, 1991) and decrease the speed. In most cases also the standard deviation of the travel time and of the speed decreases (except for the heavy traffic loads with 40% AICC with target headway equal to 1.5 s). No significant difference was found between the speed and travel time of AICC vehicles and other vehicles.

With respect to traffic safety, a decrease was found in both the number of shockwaves and the number of vehicles in a shockwave. This decrease was not found significant, due to the sample size and the large standard deviation of the random variables involved. The observation that the decrease was found in virtually all cases may be regarded as evidence for the decrease.

The distribution of TTCs indicate an increase of the TTCs, and a decrease of the fraction of TTCs less than 4 s. This is consistent with Morello et al. (1994). It can for an important part be attributed to the AICC vehicles themselves. From the distribution of headways a slight decrease was found as AICC is introduced. For the fraction of headways below 0.5 s, it was found that for AICC vehicles this fraction slightly increases. On balance, it is uncertain whether the general increase of headways and TTCs would result in an increase of traffic safety. This depends on what one could consider to be a safe headway or TTC for AICC drivers.

The study has confirmed the notion from earlier studies that AICC systems can contribute to a more stable traffic flow without sacrificing capacity. These results were found for penetration levels on passenger cars of 20% (target headway 1.0 and 1.5) and 40% (target headway 1.0). However, for 40% penetration and a target headway of 1.5 s a deterioration on the traffic performance was found at the higher levels of traffic demand: the speed collapsed, especially on the left lane. It appeared that in this case real traffic measurements could not be processed without problems, which could mean that combinations of headways, speeds and division over lanes occurring in reality cannot be achieved with traffic flows with a high penetration level of AICC with a target headway of 1.5 s.

Further research is needed to improve the understanding of how AICC will really affect driver behaviour. Several assumptions have been made in this study, based on driving simulator experiments (Hogema, Janssen & Coëmet, 1996), as to when a driver switches the AICC on or off (especially in situations where the driver must overrule the AICC), and how AICC will affect lane changing behaviour. As soon as AICC systems will become available on the market (probably within several years), they will provide the opportunity to study the interaction of driver and AICC in real world situations.

Current prototypes of AICC are based on target headways around 1.5 s. As long as the penetration of such systems is low (20%), it appears that they may be introduced without any problems for the traffic performance. The results of the present study indicate that for larger penetration levels, shorter target headways are necessary.

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