ISA EFFECT ASSESSMENT: FROM DRIVING BEHAVIOUR TO TRAFFIC FLOW

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ABSTRACT

This paper discusses two complementary methods for ISA effect assessment, and how to apply them in a coherent manner. The first level consists of the effects on individual driving behaviour, typically measured with an instrumented vehicle or a driving simulator. Results at this level form the starting point for the second level, which consists of microscopic traffic flow simulation. ISA system characteristics and behavioural effects should be incorporated in the traffic simulation model.

The main focus of the paper is on an explorative case study, in which the MIXIC model was applied to study the effects of a dynamic ISA system. The ISA penetration level was varied as an independent variable. The in-car control unit consisted of a mandatory ISA The road configuration that was studied of consisted of a lane drop from 3 to 2 lanes, and the roadside part of the ISA system determined the actual ISA speed limit based on the traffic state. The driver model was adjusted to take into account the set speed of the in-car ISA system, but otherwise, no strategic changes in driving behaviour were assumed. Results shows a decrease in throughput (volume) combined with positive effects on safety (shock waves, speed variance) when ISA is introduced. For the validation of these results more research into the driver's behaviour in the presence of ISA is recommendable.

INTRODUCTION

The application of new technologies in road traffic (Advanced Transport Telematics, ATT) may contribute to a more efficient use of the existing infrastructure for traffic and transportation, to improve traffic safety and reduce the environmental impact. Increasingly, advanced systems within cars and along the road will change the driving task considerably. Systems that inform and support the driver or even take over parts of the driving task (Advanced Driver Assistance Systems: ADAS) are emerging with perhaps a fully automated vehicle guidance (AVG) concept for the further future. For the moment, the developments especially seem to focus on in-car applications such as navigation, route guidance, Adaptive Cruise Control (ACC), Collision Avoidance, Lane Departure Warning, and Intelligent Speed Adaptation (ISA).

Effects of a new technology can be considered on two levels. Ultimately, new systems can only be successful if they perform well at both these levels.

The first is the *individual driving behaviour* level. Research methods at this level are typically driving simulators or instrumented vehicles; evaluation studies have their focus on driving behaviour, workload, and acceptance.

The second level is the *traffic flow* level. If one wants to estimate the effects of a new technology before implementing it in real traffic, the method to be used is traffic simulation. Using simulation, effects of a new system on traffic performance and traffic safety indicators can be systematically studied. When considering ADAS or AVG systems, the role of the driver typically changes to a certain extent from directly controlling the vehicle's motion to supervising the system's performance, possibly having to intervene in situations where the system's behaviour deviates from the driver's intended behaviour. At the same time, the ADAS takes over the role of the primary vehicle control (e.g. gas and/or brake pedals). When the system is known to have effects on driving behaviour (e.g. in terms of speed choice, car-following behaviour, lane-change behaviour, etc.), these effects should be incorporated in the model. Microscopic traffic simulation models, distinguishing separate driver and vehicle sub-models, offer the level-of-detail required to model these changes in the system.

This paper describes a part of a study that was performed by TNO under contract with the Dutch Ministry of Transport, Public Works and Water Management. This study explored how and to what extent communication among vehicles or between vehicle and infrastructure can contribute to a more stable traffic flow for better throughput and safer driving on highways. The effect of a dynamic ISA system was explored in a simulation of traffic on a motorway with a bottleneck due to a lane drop from 3 to 2 lanes.

METHOD

MIXIC

The study was conducted using the microscopic traffic simulation model MIXIC (Van Arem, De Vos, & Vanderschuren, 1997). This model has been developed in a joint effort by TNO and the Transport Research Centre (AVV) of the Ministry of Transport, Public Works and Water Management.

MIXIC (Microscopic model for Simulation of Intelligent Cruise Control) was specifically designed for analysis of the impact of automated systems, which partly take over driver tasks. The first application of MIXIC was to analyse the impact of Adaptive Cruise Control (ACC) on traffic flows. Several studies involving ACC were conducted (Van Arem, Hogema, Vanderschuren, & Verheul, 1995; Van Arem, De Vos, & Vanderschuren, 1997; Hogema, & Van der Horst, 1998). The latest application of MIXIC has been the exploration of the impact of ISA and Co-operative Following and Merging (CFM) (Tampère, Hogema, Van Katwijk, & Van Arem, 1999).

MIXIC simulates traffic on a link level in a network. Given an input of traffic flow, MIXIC simulates traffic behaviour on this link and produces traffic statistics. As input, MIXIC uses real-world traffic measurements. In each time step (set to 0.1 s) new vehicle positions are calculated by a driver model and a vehicle model. The driver model produces driver actions, such as lane changing and new pedal and gear positions. These driver actions are input for the vehicle model, which calculates the resulting acceleration and position of the vehicle. MIXIC consists of the following components:

- A traffic generator, generating vehicles at the start of a link.
- A link model, which gives relevant link data to which vehicle positions can be related.
- A traffic evolution model, which describes the movements of the vehicles. This model is induced by the individual vehicle and driver models.
- A data collection component, gathering microscopic output parameters.

Traffic generator

The traffic generator decides when to place new vehicles at the start of the first road link. Vehicles are generated from so-called traffic 'injection' files and are assigned specific vehicle/driver parameters and an initial state. A traffic injection file consists of recorded real-world data of individual vehicles (arrival time, position, lane, speed and length). Also vehicle types and driver types (reaction time, desired speed, etc.) are assigned randomly (using occurrence frequencies). The use of injection files to generate input for a microscopic model has three advantages. First, it is fast and does not require elaborate studies into vehicle generators and their validity. Second, it puts the traffic evolution model to the test, as the model should in any case be able to process the amount of traffic offered by the injection file, being traffic actually observed. Third, it allows for calibration and validation by comparing the model's downstream results with real-world measurements further downstream.

Driver model

The driver model consists of three main components: the lane-change model, the longitudinal model and a component that describes the interaction between the driver and the ADAS.

The lane change model consists of a mandatory lane change model (represents forced lane changing due to geometric factors) and a free lane change model (represents overtaking). The longitudinal model distinguishes free-driving behaviour (where the driver attempts to reach or maintain his intended speed) and car-following behaviour (where the driver adjusts his speed and / or following distance with respect to vehicles ahead). The car following model implemented in MIXIC is derived from the Optimal Control Model of Burnham, Seo and Bekey (1974) and is based upon the assumption that drivers try to keep the relative speed to the lead car zero and simultaneously attempt to keep the distance headway at a desired value. In addition to the original model, also the relative speed to the vehicle ahead of the lead vehicle is taken into account because it contributes to the stability of the traffic flow. In contrast with other microscopic traffic models, in MIXIC it is possible to specify the driver interaction with an ADAS.

Vehicle model

The vehicle model describes the dynamic vehicle behaviour as a result of the interaction with the driver and the road, taking into account the ambient conditions. 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 model is an updated vehicle acceleration, which is used to calculate a new speed and position of the vehicle.

Vehicles are removed from the MIXIC simulation in the case of a simulation conflict ("physical overlap" of vehicles) or in case of a failure to merge.

ISA

ISA systems can be categorised in several dimensions, e.g. the system status (advisory versus mandatory) and the speed limit status (fixed, variable or dynamic), see e.g. Carsten and Fowkes (1998). Given the focus of the project on vehicle-vehicle or vehicle-roadside communication, a dynamic version was a logical choice. The dynamic aspect consisted of the ISA speed limit being varied as a function of the traffic state. In order to examine the potential maximal impact of ISA on traffic flow, it was decided to focus on a mandatory in-car ISA system.

The in-car part of the ISA system implemented in MIXIC consisted of a controller that calculates the gas pedal position that would be needed to accelerate to the ISA-speed limit. The actual gas throttle position that is fed into the vehicle model is the minimum of the gas pedal position that would be set by the driver in absence of any ISA system and the pedal position set by the ISA controller. Thus, the driver is overruled by the ISA controller when he tries to accelerate to speeds higher than the ISA speed limit. The result is a mandatory ISA system.

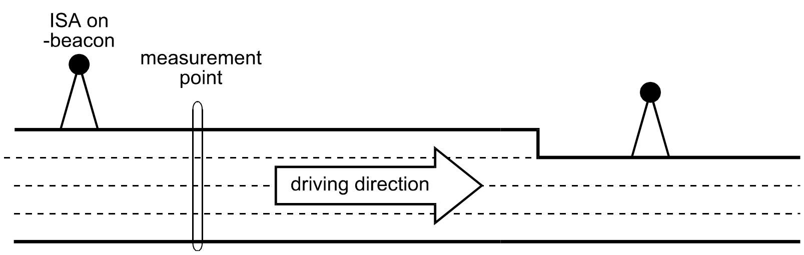


Figure 1 Lay-out of the ISA road-side system

The road-side part of the ISA system used an algorithm that was fed with data from a single measurement point (see Figure 1). The algorithm that was used in this study had an anticipating nature. It used data from one measurement point, located upstream from the bottleneck where traffic flow should be smoothened by ISA. Two beacons are used: the first one was located upstream of the bottleneck and intends to set the speed limit when necessary; the second one was located downstream of the bottleneck and switches the system of passing ISA-vehicles off again.

Non-ISA drivers would in practice be informed about the current speed limit, e.g. through Variable Message Signs (VMS). However, for this study this was not modelled. In fact the simulations therefore represent a 'worst case' scenario with a highly heterogeneous mixture of restricted ISA-drivers and non-informed normal drivers. Thus, the impact on the simulation can solely be attributed to ISA and not to the response of non-ISA drivers to VMS.

The logic of the ISA-algorithm was inspired by existing algorithms for ramp metering in the Netherlands (Van Velsen, & Stevens-van der Geer, 1996). The rationale behind speed adaptation can be explained on the basis of Figure 2. This figure shows a typical relationship between the speed and the occupancy as measured in MIXIC. Occupancy of a point on a lane is defined as the percentage of time that the point is covered by traffic. The occupancy of a lane is closely related to the density but has the advantage that it is defined for a point on the road instead of along a certain distance and therefore it can easily be measured directly (e.g. by inductive loop detectors).

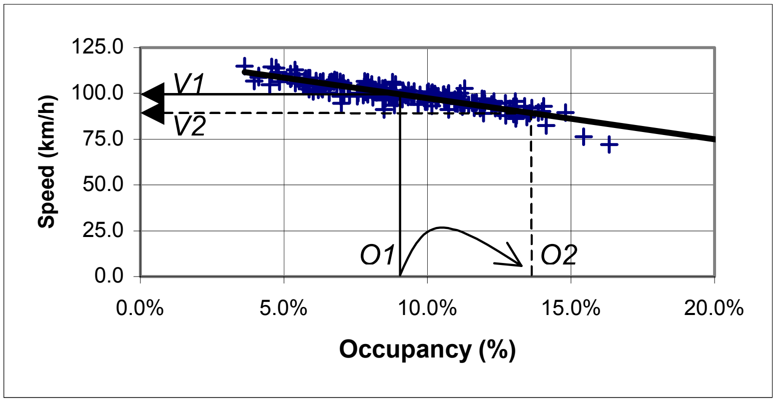


Figure 2 Occupancy-Speed relationship of non-ISA traffic on 2-lanes ('+'-markers indicate occupancy and speed aggregates per minute; the solid line is a fitted linear curve).

The occupancy-speed relationship of a cross-section is always decreasing in nature and hardly varies with the number of lanes in the cross-section. Suppose traffic with occupancy O_1 on the 3-lane road (N_1=3) approaches a lane-drop with speed V_1 (a point on the curve in Figure 2). If the same volume wants to flow into the 2-lane section (N_2=2) then density (and hence: occupancy) has to increase with a factor N_1/N_2 = 3/2. The occupancy O_2 then equals 1.5 * O_1 and the speed V_2 with which the traffic can be processed on the 2-lane section can be read from Figure 2.

This is the principle of the ISA-algorithm. Referring to Figure 1, the occupancy O_1 is measured by the ISA observer aggregated over a user-defined time interval (e.g. 1 minute). The ISA algorithm uses a parameterised Occupancy-Speed curve to calculate the speed V_2 according to the above mentioned principle. The resulting ISA-speed is smoothened before transmitting it via the first beacon to prevent that subsequent speed limits differ too much.

As to changes in driving behaviour due to ISA, the driver model took into account the state (on/off, set speed) of the ISA in the lane change decision models. This prevented, e.g., free lane changes with the intent to overtake another vehicle if the actual overtaking manoeuvre would be inhibited by the ISA system. Otherwise, it was assumed that there would be no changes in driving behaviour (speed choice, car-following behaviour, free or forces lane-changing behaviour) due to ISA.

Experimental set-up

The road configuration that was used in this study is a bottleneck due to a left (fast) lane drop from 3 to 2 lanes (see Figure 3). The road consists of 6 links of 1000 m each. In the middle of each link a measurement point is located for statistical analysis. The ISA road-side system is located on links 3, 4 and 5. The ISA observer measures occupancy at the beginning of link 4. The ISA-speed limit is transmitted by a beacon on link 3 located 1700 meter before the lane drop. The 'off'-beacon is located in the middle of link 5.

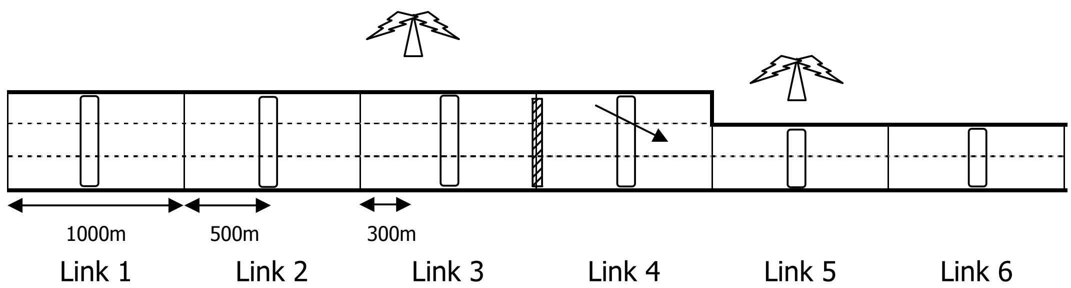


Figure 3 Road configuration for the ISA simulation

The traffic demand is specified by an injection file containing inductive loop measurement data from the A2 motorway between Utrecht and Amsterdam in the Netherlands. The injection file was assembled so that the traffic volume increases stepwise from low traffic load to values near capacity (for 3 lanes). The total simulated time was 4 hours. During the last hour, the average volume raises gradually to 6500 veh/h to make sure that capacity of the bottleneck was reached by the end of the simulation.

The independent variable was the ISA penetration level in cars. This variable was varied from 0% (i.e. the reference condition) to 50% in 10% increments.

RESULTS

The three highest observed traffic volumes (using 5-minute interval observations) over the entire simulation on link 5 are shown in *Figure 4* as a function of ISA penetration level, expressed in passenger car units (PCUs).

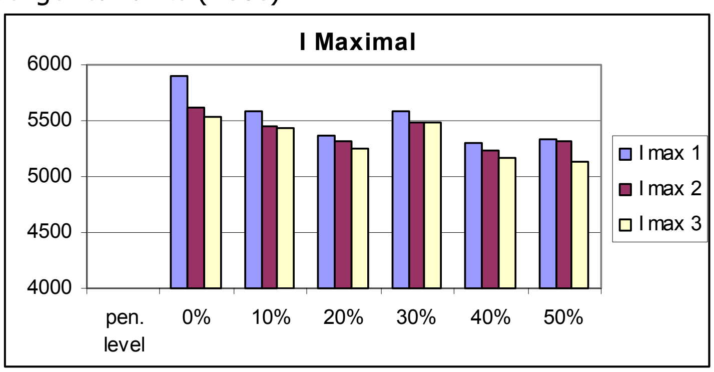


Figure 4 Three highest observed traffic volumes (PCU/hr) over the entire simulation (Link 5).

The data showed a decrease of the maximum intensity with increasing ISA penetration levels. The maximum observed traffic volume decreased down to -400 PCU/h or –7% for the variant with 50% ISA vehicles. The explanation of the poor traffic performance with ISA is not trivial. The homogeneity – that could have a positive effect, in that the align-to-gap manoeuvre has to overcome smaller speed differences between lanes – could also aversely affect the process: when speeds are too homogeneous then the capability of accelerating to gaps alongside disappears. Possibly the negative effect comes into play in the simulation. This could be due to the restrictive nature of the ISA in-car controller.

The mean speeds over the first 3 hours of simulation are shown in Figure 5 for link 4 and link 5.

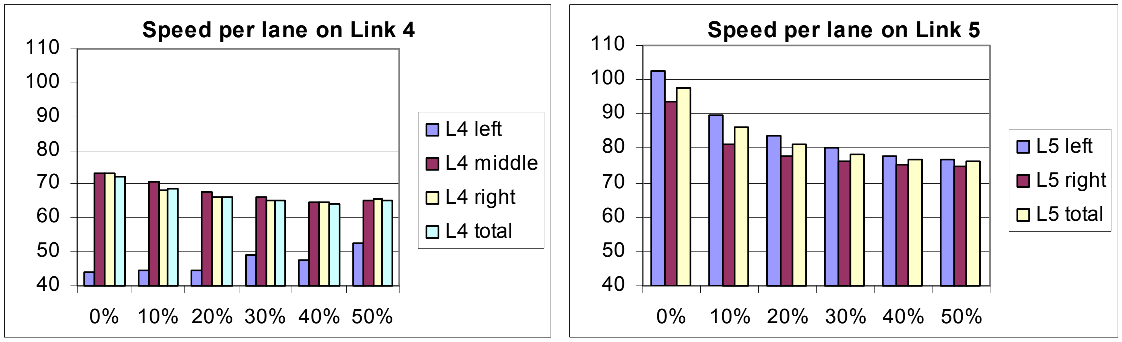


Figure 5 Average speeds over link 4 and link 5

It is clear from Figure 5 that the speed decreases as more ISA-vehicles are present. This is an expected result. The merging process on link 4 apparently sinks the speed on that link far below the ISA speed limit. Still the influence of ISA is clear. Especially the speed of the few vehicles on the leftmost lane is higher than in the reference variant without ISA. On link 5 vehicles drive faster than on link 4, but still, the speed decreases with increasing penetration levels. On both links, the speed differences among lanes decline with increasing penetration levels.

Another part of the explanation of the poor traffic performance with respect to throughput could be found in the division over lanes (Figure 6).

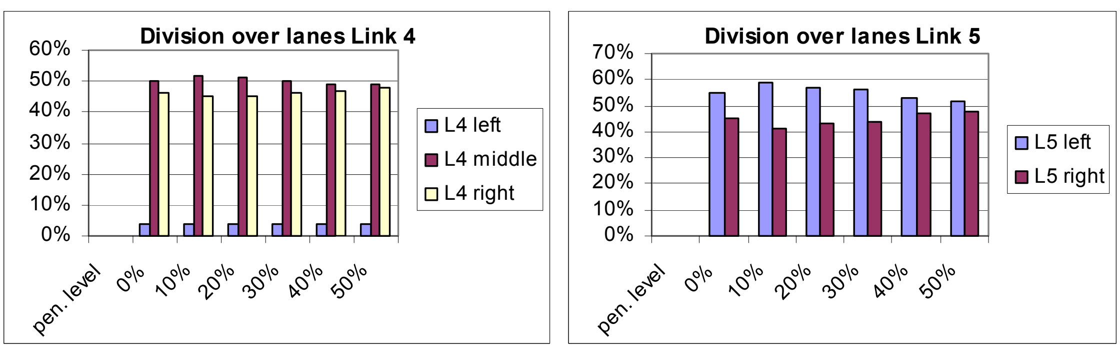


Figure 6 Division over lanes on link 4 and 5

The introduction of ISA in small fractions initially enlarges the difference in load per lane. Further increasing the penetration level reduced the difference decreases, until with 50% of ISA-vehicles the difference in load is minimal. Possibly the initial division over lanes in the reference variant is more or less ideal with respect to throughput. Statistical analysis with several simulation runs per variant should point out whether it is a coincidence that the variant with 30% – where the division over lanes is equal to that of the reference – is the only ISA-variant with a higher average and maximal traffic volume.

One of the most revealing criteria of traffic safety is the number of conflicts. On link 4 this number is inextricably related to the number of failures to merge. Both criteria are presented in Figure 7.

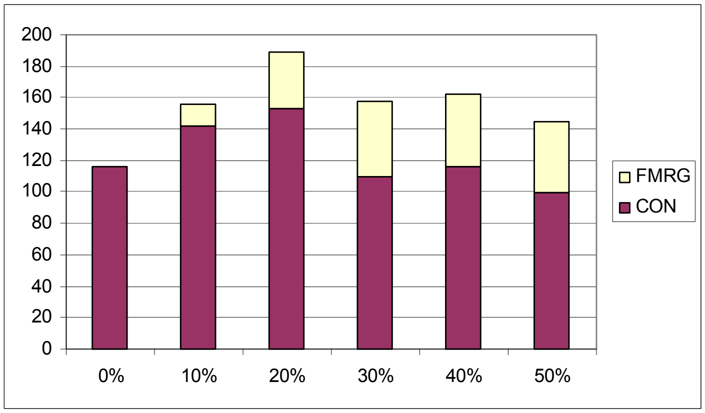


Figure 7 Number of simulation conflicts (CON) and the number of failures to merge (FMRG) on link 4.

The two criteria can first be analysed separately. The number of removed vehicles due to conflicts seems to increase with the introduction of a limited number of ISA vehicles but with higher penetration levels the number of conflicts is comparable to the reference case. It seems that the safety of the merging process is hardly influenced by ISA. However, the failures to merge show an increase with penetration level until it stabilises from 30% on. This is an indicator that the merging process gets more difficult when ISA is introduced.

The combination of the criteria leads to non-systematic differences between variants. This observation can be interpreted as a kind of trade-off between forced mandatory lane changes that lead to conflicts and mandatory lane changes that can not be executed due to safety reasons. Indeed a forced lane change manoeuvre by the vehicles that now fail to merge might have caused as many conflicts as in the reference case.

The overall number of conflicts and failures to merge together is higher than the reference in all variants which is an indicator for unsafety or inefficiency in traffic flow during the merging process.

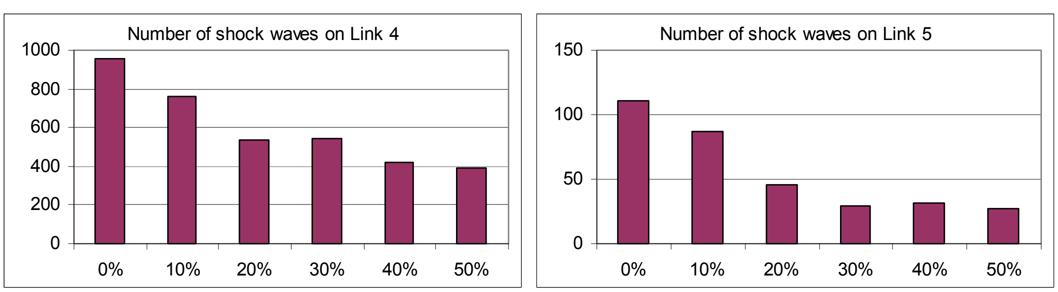


Figure 8 Number of shock waves on link 4 and 5 (NB: the vertical scales in these graphs are different)

This conclusion is contradicted by the shock wave data. Figure 8 shows that there is a sharp decrease in the occurrence of shock waves with the introduction of ISA on link 4 as well as link 5.

The number of shock waves should be interpreted in combination with the number of vehicles involved in a shock wave. Table 1 reveals that with the gradual introduction of more ISA vehicles, the number of vehicles and observations of accelerations < -5.0 m/s^2 within a shock wave increases. The combined effect (less shock waves with more vehicles involved) can be seen in Table 1 as well: the total number of vehicles or observations of accelerations < -5.0 m/s^2 within a shock wave are listed as 5-min. averages. Both show a declining tendency with penetration rate.

Table 1 Shock wave severity information for link 4 (first 3 hours of simulation)

	Vehicles involved		Observations < –5.0 m/s^2	
	average per shock wave	average per 5 min	average per shock wave	average per 5 min
0%	5.3	146	35.9	981
10%	6.3	137	47.4	1031
20%	7.2	110	59.6	913
30%	7.0	109	49.9	780
40%	7.9	95	64.5	780
50%	8.3	93	72.5	814

As a conclusion there are indicators that ISA leads to safer traffic in the MIXIC simulation indeed, but not so drastically as the reduction in the number of shock waves suggests. The increasing number of failures to merge suggests inefficiency in the merging process.

The fact that there are significantly less shock waves but with more impact in terms of vehicles involved could be explained by assuming that the introduction of ISA limited cars leads to platoons of vehicles behind ISA vehicles that block the road for those who want to drive faster. The homogeneous nature of these platoons results in fewer shock waves, but once they do occur, there are more vehicles involved because there are fewer large inter-vehicle spaces in which shock waves could be absorbed.

The validity of this assumption can be investigated by looking at the headway distributions (*Figure 9*). On link 4, the presence of ISA-vehicles causes the average headway of non-ISA vehicles to shift to lower values. At the same time, the ISA vehicles have significantly larger headways. This confirms the assumption that platoons of vehicles with higher desired speeds (non-ISA) are formed behind a slower platoon leader (limited due to ISA). Indeed this effect becomes more pronounced when more ISA vehicles are present (10% vs. 50% in *Figure 9*).

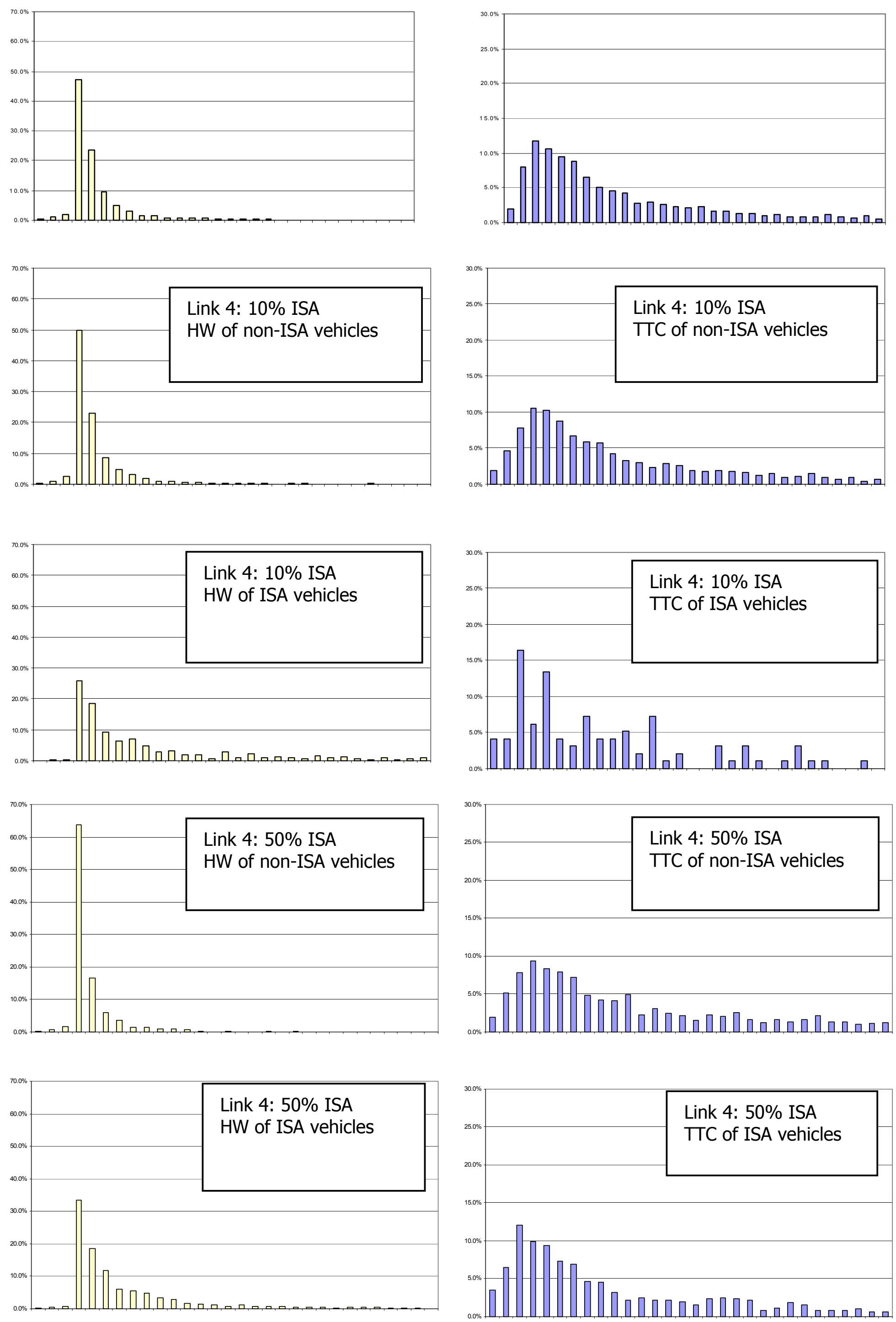
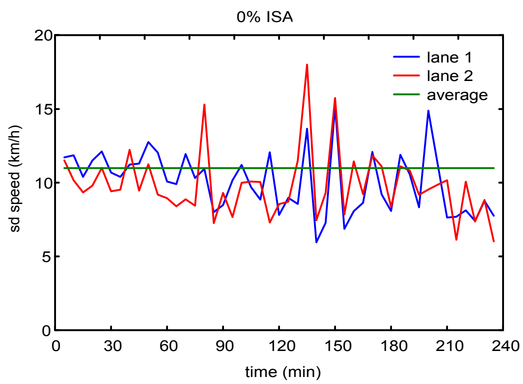


Figure 9 Headway (HW) and Time-To-Collision (TTC) distributions during the 3rd hour of simulation with 0%, 10% and 50% ISA. (Time categories on the x-axis are 0.25 s and 1.0 s wide for HW and TTC respectively).

The distribution of the Time-To-Collision (TTC) is plotted in Figure 9 as well. This distribution remains more or less constant, regardless of the proportion of ISA vehicles. The explanation lies in the nature of the TTC, which is a combination of headway and speed difference. As discussed above, headways tend to become smaller with increasing ISA penetration levels. The unchanged TTC then can only be explained due to smaller speed variations within lanes.

This is indeed the case. Figure 10 plots the speed variance on link 5 (on link 4 the speed variance is distorted by the occurrence of shock waves and the merging process). It is clear that in the three last hours (when traffic is busier and the ISA algorithm has most influence) the standard deviation has dropped from approximately 10 km/h in the reference case to about 4 km/h with 50% ISA.



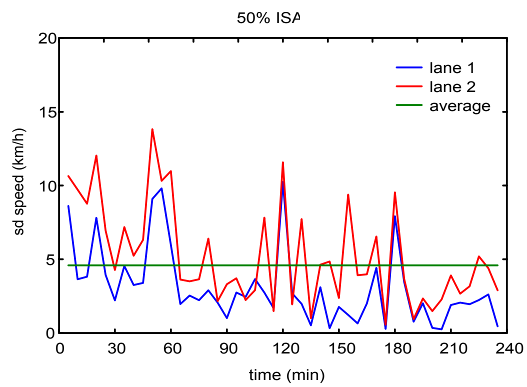


Figure 10 Speed variance on link 5 as a function of time (5-minute intervals) (Left: 0% ISA; Right: 50% ISA)

DISCUSSION AND CONCLUSIONS

The focus of this traffic simulation study was to explore the effects of the ISA penetration level. Therefore, the results are exploratory en the sense that no optimisation has been conducted in terms of roadside system (number and locations of beacons, algorithm) or in-vehicle control system. Thus, the results of this study should not be generalised beyond these restrictions.

The simulation results with MIXIC indicate that traffic flow is more homogeneous after the introduction of ISA vehicles. This conclusion holds even though non-ISA drivers are not informed about the current speed limit. The homogeneity of traffic flow can be noticed from:

- a reduced variance of speeds among lanes
- a reduced variance of speeds within lanes
- a more balanced division of flow over lanes

Traffic performance in the simulation might be affected negatively by ISA in the situation studied here. Indicators that point in this direction are:

- a lower maximum observed traffic volume
- a higher number of failures to merge

Traffic safety criteria indicate an increase in traffic safety:

- the number of vehicles involved in a shock wave decreases
- the variance of the speeds within a lane decreases
- the average speeds decrease

The homogenisation of traffic, as well as the safety benefits can be understood from the characteristics of the ISA system.

There are several possible explanations for the negative effect on throughput. It might be inherent to a restrictive ISA controller that a driver has problems in utilising gaps further downstream in absence of the ability to accelerate above the speed limit when driving in strongly homogenised traffic. On the other hand, drivers may change their behaviour in several ways to overcome this problem. Especially the forced lane change procedure (due to a lane drop ahead) could be changed in several ways due to the introduction of ISA, e.g.

- how far ahead of the lane drop a driver starts to look for, and tries to reach, a suitable gap;
- the way in which a driver tries to reach a suitable gap;
- gap acceptance criteria with respect to the new lead vehicle as well as the new follower vehicle.

Such changes are not known yet and therefore not included in the model. This may affect the validity of the mandatory lane change model of MIXIC in the presence of external speed control like ISA.

This illustrates the need to study individual driving behaviour effects and traffic flow effects in a coherent manner. Only once the effects of new systems on driving behaviour are understood, they can be incorporated in microscopic traffic flow models. This iteration in both research methods is required to bring the traffic simulation results from a first exploration of effects to an accurate prediction of effects on a traffic flow level.

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