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Traffic flow effects of Integrated full-Range Speed Assistance (IRSA)

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Abstract— **This paper discusses the assessment of the effects of Integrated full-Range Speed Assistance (IRSA), using the ITS modeller. The aim of IRSA is to assist drivers in their longitudinal driving task by providing speed advice or speed warnings and cruise control-like functionalities. The effects of the application of IRSA in three scenarios (Approaching a traffic jam, Approaching a reduced speed limit zone and Leaving the head of a queue) are presented. Positive effects on throughput, safety and the environment were achieved. In addition, the paper discusses general aspects of modeling vehicle and driver behavior for co-operative systems, and how this is done in the ITS modeller.**

I. Introduction

SPEED is one of the key factors in road traffic. It is positively associated to the quality of travel: a high speed implies a short travel time. However, a high speed can also lead to high accident risk or high emission of exhaust gas and noise. The speed of a vehicle is traditionally controlled by the driver, who takes into account local traffic conditions as well as applicable speed limits. However, decisions by the driver are sensitive to judgment and operational errors. Many accidents are speed-related and partly due to human error. In cases of congestion, human drivers are typically poor controllers.

Advanced Driver Assistance (ADA) systems are systems that support a driver in his driving tasks. An example of an ADA system that is commercially available is the Adaptive Cruise Control (ACC) system: by extending a 'regular' cruise control system with a radar sensor, the vehicle can maintain a preset speed, but also adapt the speed to a slower predecessor. In addition to sensors on the vehicle, ADA systems can also use wireless communication systems to receive information from road-side systems and other vehicles. Combined with ACC, this makes CACC.

In order to support the development of ADA systems, TNO started the SUMMITS program with the objective to develop and demonstrate an integrated tool set – the *"SUMMITS Tool Suite"*. The SUMMITS Tool Suite allows developers of ADA systems to assess issues regarding technical functioning, human factors and traffic flow in a consistent way.

The Integrated full-Range Speed Assistant (IRSA) was selected as a case to guide and test the development of the Tool Suite. The IRSA system is a collection of functions to support a driver in maintaining an appropriate speed in a number of selected traffic conditions, such as approaching a traffic jam, cut-in situations and leaving the head of the queue at a traffic light.

The following overall research questions were defined in the IRSA project:

- To what extent can cooperative driving, achieved through vehicle to vehicle and vehicle to infrastructure communication, contribute to improved traffic and system safety, improved throughput, improved environmental aspects (gas emissions and noise) and improved driver comfort and safety perception, and add value to existing ADA functionalities (ACC, Stop&Go, Forward Collision Warning, Lane Departure Warning)?
- What implementation issues exist, in the areas of robustness/graceful degradation, stepwise introduction (from 0% to higher penetration levels), structured design methodologies and expected social benefits under different circumstances? In the IRSA project, these questions are considered on three different levels: traffic flow level, cluster level and vehicle level.

This paper discusses the traffic simulations carried out to investigate the traffic flow effects of IRSA, for different penetration rates. It is organized as follows. In section II, an overview of the international state of the art of studies about the impacts of ACC systems on traffic flow is given. In section III, the IRSA system and the scenarios that were investigated are described. In section IV, a brief introduction to the ITS modeller and how IRSA was modeled is given. Section V discusses the results of the experiments with IRSA in the ITS modeller. Section VI contains the conclusions and recommendations.

II. International state of the art

The impacts of the use of Advanced Driver Assistance systems on traffic flow characteristics have been subject of research since the late 90-ies. In particular the impacts of Adaptive Cruise Control were studied extensively using traffic flow simulation models [1, 2]. ACC can contribute to smoother traffic flows, because it is able to accelerate and decelerate more gently and precisely than human drivers can. Whether the use of ACC will increase roadway capacity depends strongly on the headway setting of the ACC

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compared with human driving. Minderhoud [3] concluded that ACC systems with a time headway setting below 1.2 s can increase the road capacity. The overall conclusion of the studies up till now is that ACC can improve traffic safety by improving the traffic flow stability, but that the direct gains in traffic flow efficiency are limited (indirectly, fewer accidents lead to less congestion and thus improved efficiency).

A disadvantage of ACC is that it will react only to the vehicle directly in front of the ego-vehicle. This raises concerns regarding traffic flow stability, which can be improved by also using information about vehicles further downstream. In [4] a cooperative following system was studied which uses automated longitudinal control combined with inter-vehicle communication to anticipate severe braking manoeuvres. Microscopic simulations revealed that a better platoon stability was achieved, but the potential advantages on traffic flow efficiency could not be confirmed. Very recently, an ACC strategy was proposed that adapts the ACC driving style to the traffic situations determined by inter-vehicle or roadside-vehicle communication [5, 6]. When approaching a traffic jam, the ACC system increases the traffic safety by earlier braking. When arriving at the bottleneck section and when leaving the traffic jam, the maximum acceleration increases while the time headway decreases, both to increase the bottleneck capacity. Microscopic simulation results showed that already a small amount of 'traffic-adaptive' ACC vehicles improved the traffic stability and performance.

Concluding, it can be stated that the impacts of 'autonomous' ACC on traffic flow characteristics have been studied quite extensively. There is a need to extend this field of research to ACC systems that also make use of information from other vehicles and/or road infrastructure. This field has been hardly addressed so far.

III. THE IRSA-SYSTEM AND SCENARIOS

A. Modes and functions

IRSA can be used in different ways: as a purely advisory system, as a system that partly intervenes in the vehicle controls (e.g. by a haptic throttle), or as a controlling system that fully controls the longitudinal speed of the vehicle. The driver determines in which way he will use IRSA by selecting a mode of operation of the system. The possible modes of operation are IRSA off, IRSA advisory mode, IRSA intervening mode and IRSA controlling mode.

In all modes, the IRSA system computes a desired acceleration. In the advisory and intervening mode, this desired acceleration by the IRSA system is presented to the driver in some form, e.g. a speed advice or a haptic gas pedal setting. The driver will react to these signals, and give a new desired acceleration to the vehicle by pushing the gas, brake or clutch pedals. In the controlling mode, the desired acceleration by the IRSA system is given directly to the vehicle.

From an abstract or systems engineering point of view, the major difference between the controlling mode and the advisory/intervening modes is that there is no driver that 'distorts' the acceleration computed by the IRSA system in the controlling mode. Hence, in designing and modeling the IRSA system, the focus will be on the controlling mode. Different settings and communication strategies have been experimented with (e.g. the minimum headway setting or the number of preceding vehicles' speeds taken into account).

B. Scenarios

The IRSA system was tested in several scenarios. On the traffic flow level, these were (i) Approaching a traffic jam, (ii) Approaching a reduced speed limit zone, and (iii) Leaving the head of a queue. In the first two scenarios, the aim of IRSA was to help the driver slow down in a safe and comfortable way, in the last scenario the aim was to help drivers accelerate in an efficient way, to improve the safety and throughput at traffic lights.

These scenarios were modeled in the ITS modeller. This paper describes one of the scenarios, Approaching a traffic jam, in more detail. The results of the other scenarios are described briefly.

In other parts of the SUMMITS program, more experiments were carried out, with different simulation tools, in laboratory conditions and on the road. The aim of these experiments was, among others, to assess the fault tolerance of the system, driver reactions and acceptance, and string stability. For an extensive description of all the experiments carried out and the tools used, see [7, 8, 9].

C. Approaching a traffic jam

In this scenario, the reference situation is a three-lane motorway with a lane drop halfway. The traffic is near-capacity, so congestion occurs near the lane drop. The hypothesis is that IRSA can help to improve the safety and/or reduce the congestion by warning the drivers and helping them (or the vehicles, in the controlling mode) to slow down in a safe and comfortable way, so that they drive at an appropriate speed when they arrive at the congested section.

When vehicles are driving at speeds below 70% of the speed limit, vehicles equipped with IRSA send out warning messages. IRSA vehicles within 200 meters of the sending vehicle will receive the messages. Only upstream IRSA vehicles will use the information of the messages. The system will start braking when the speed is at least 10% higher than the speed of the sending vehicle, with a constant deceleration based on the speed of and distance to the sending vehicle.

Next to this communication system, IRSA uses an adaptive cruise controller to control its speed automatically, taken into account the positions of the preceding vehicles. When only the direct predecessor is taken into account, a basic ACC controller is used. By using vehicle-vehicle communication, more downstream vehicles can be taken into account and combined into a cooperative ACC controller (CACC).

For the controlling mode, the following versions of the ACC and CACC controllers where tested for penetration rates of 20, 50 and 100%:

ACC: Basic ACC controller, which tries to maintain a reference distance to the predecessor and tries to minimize the speed difference with the predecessor.

CACC1: CACC controller, in which the resulting acceleration is computed by determining the individual ACC acceleration with the basic ACC controller in relation to a number of preceding vehicles (equipped with the system), and by taking the minimum of these individual ACC accelerations. The number of predecessors (equipped with the system) taken into account is 3. The distance and speed of the first predecessor vehicle (IRSA equipped or not) are measured with the vehicle's own sensors (radar). In addition to the characteristics of that vehicle, the characteristics of the first two IRSA-equipped vehicles are taken into account. See Fig. 1.

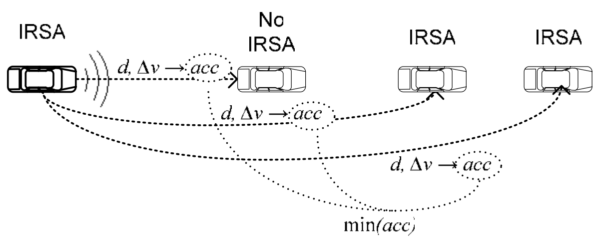

Fig. 1. Basic CACC controller of IRSA

CACC2: adapted version of CACC1, which controls on the speed difference with the direct predecessor, added with a term based on the average speed difference with a number of slower predecessors (equipped with the system). The number of predecessors (equipped with the system) taken into account is 3. The advantage of this method compared to CACC1 is that no distance headway needs to be determined, which is hard in case the penetration rate of the system is less than 100%. See Fig. 2.

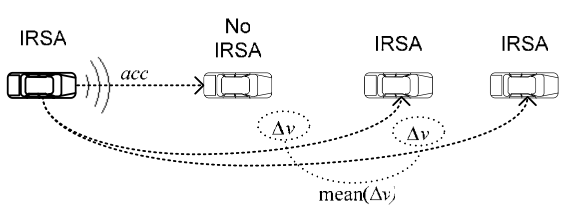

Fig. 2. CACC2 controller of IRSA

CACC1+: Added to the vehicle-vehicle communication which is used by all CACC controllers, extra vehicle-vehicle communication is implemented in this version (vehicles send messages when speed drops below 70% of the speed limit, as described above).

CACC2+: CACC2 extended with the same (extra) communication system as CACC1+.

In the advisory mode, the system advises the drivers of these vehicles when to start slowing down, and how hard to brake. The system advices to start braking when the speed is at least 10% higher than the speed of the sending vehicle, equal to the controlling mode. Ideally, the deceleration is achieved by just releasing the accelerator pedal. However, we assumed that the driver will brake with the same constant deceleration as in the controlling mode (the difference is that in the advisory mode, the vehicle is not equipped with an ACC or CACC system).

D. Approaching a reduced speed limit zone

Reduced speed limits can be applied for several reasons, e.g. to improve air quality or safety, or to smoothen traffic and avoid congestion. In this scenario, inspired by the implementation of a reduced speed limit on the A13 motorway in Overschie (Rotterdam) to improve air quality and reduce noise annoyance [10], there is a reduced speed limit (from 120 km/h to 80 km/h). This large difference in speed limits may cause shockwaves as drivers brake hard when they enter the section. The hypothesis is that IRSA can support the driver to slow down in a safe and comfortable way (earlier than they normally would), by giving speed or deceleration advice. In some cases, this may prevent congestion. The reduced speed limit and the location of the start of the reduced speed limit zone is communicated to the equipped vehicles by two road-side beacons: one located 1200 meters before the start of the reduced speed limit zone and one located at the start of the reduced speed limit zone. Vehicles within 300 meters of a beacon can receive the messages. The IRSA system will remember the content of the messages as long as necessary. See Fig. 3.

In the controlling mode, the vehicle will slow down automatically by the IRSA system. The IRSA deceleration was determined using measurements of braking maneuvers, measured with instrumented vehicles on a real motorway, where test persons were asked to brake as they would normally do if they had the opportunity to slow down in a smooth and comfortable way when the speed limit changes. The shape of the measured braking curve was approximated and incorporated in the braking algorithm of IRSA.

In the Advisory mode, the driver receives a warning to start braking for the reduced speed limit. In our simulations, we assumed that drivers start braking later than the controlling mode version of IRSA, but earlier than without the system. Two versions were compared: IRSA "far" (with drivers starting to brake quite early) and IRSA "close" (with drivers starting to brake quite late). Some variation in the moment when drivers start braking was introduced in both versions, as the drivers' reaction time to the advice will vary.

Penetration rates of 20, 50 and 100% were tested.

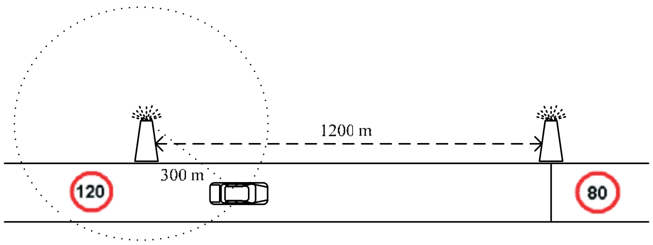

Fig 3. Approaching a reduced speed limit zone

E. Leaving the head of a queue

The Leaving the head of a queue scenario differs from the two previous ones in that it focuses on acceleration, not deceleration. The scenario is elaborated for a traffic light. The hypothesis was that IRSA can help vehicles or their drivers accelerate in a safe and efficient way. Two different settings were tested (for penetration rates 20, 50 and 100%), which were tuned to improve throughput or safety (as there appears to be a trade-off between these two aspects; faster acceleration may increase throughput but may decrease safety).

The first setting of IRSA is the basic CACC controller of IRSA. These settings result in a rather slow accelerating from standstill. Therefore, another version of IRSA was simulated with optimized parameter settings for accelerating from standstill, referred to as IRSA turbo. Furthermore, a simple ACC controller was implemented which was expected to perform good in this scenario. This controller tries to keep the headway to a fixed value, therefore this controller is refered to as 'fixed headway'. This was based on the assumption that keeping a minimum fixed time headway is necessary for safety reasons.

In practice, this could be an advisory or intervening version, which encourages the driver to accelerate quickly while alerting him only when he accelerates too fast and the headway with the predecessor becomes too small.

The reference scenario was calibrated such that the average acceleration from 0 to 20 km/h is 1.9 m/s^2, which is reported in [11] and [12] as the average (measured) real-world value.

IV. Developing and Modeling IRSA in the ITS Modeller

A. The SUMMITS tool suite and the ITS modeller

The SUMMITS tool suite consists of different tools that cover specific aspects of cooperative vehicle-infrastructure systems varying from traffic flow analysis to assessment of human factors and from dependable cooperative control architectures to fault tolerant hardware implementation. These tools are the following:

- Driving simulators and instrumented vehicles;
- MARS, PreScan and the ITS modeller: Simulation environments for the design and evaluation of the next generation of intelligent vehicles, suitable for different traffic and technical levels.
- VEHIL (VEhicle Hardware In the Loop): TNO's laboratory for testing and development of intelligent vehicle systems with moving bases.

More information on these tools can be found in [13].

The ITS modeller is a modeling environment that can simulate intelligent transport systems. Several roadside and in-vehicle systems, as well as cooperative systems, have already been incorporated in the model. New systems can be modeled easily and added to the ITS modeller. The ITS modeller functions as a shell for several commercially available traffic simulation tools. The basic vehicle and driver model in the ITS modeller, which is used as reference for the IRSA simulations, originates from the MIXIC model as described in [14].

The effects of ITS systems can be evaluated directly in the simulation model's interface (which can be set to show specific characteristics of the traffic flow, e.g. vehicles changing color when they are braking hard), and with the evaluation modules of the ITS modeller. The traffic throughput module computes figures on route flows, route travel times, total network journey times and delays, speeds et cetera. The safety module produces statistics on the number of shock waves, times-to-collision and time headway intervals. The noise production module computes the noise production levels of different types of vehicles. In addition to this, the output of the ITS modeller can be used to calculate emissions of pollutants (with TNO's detailed emission model VERSIT+).

B. Developing a common mathematical model for IRSA

In the first stage of the development of the IRSA system, a common mathematical model (the *meta-model*) was set up by a team of people with different backgrounds and expertise, among them traffic and automotive engineers, psychologists, mathematicians. They considered the vehicle, cluster and traffic flow levels and defined the IRSA-system in such a way that all 'levels' could work with the same meta-model. In other words, the same IRSA-system is assessed in the ITS modeller, the driving simulator or in an experiment on the road (albeit with different levels of detail in the algorithms).

The meta-model was implemented in the ITS modeller for the different modes of IRSA (advisory, intervening and controlling). In Fig. 3, the relation between advisory, intervening and controlling mode is shown schematically. In order to be able to model the blue (middle) box in Fig. 3 (for the advisory or intervening mode), expert judgments and experiments with e.g. the driving simulator are needed to define the drivers' reactions to the desired accelerations or speed advices given by the IRSA system. The main question to be answered is how the driver reacts at the moment he receives the message, and how this depends on the message, the human-machine interface (HMI) and the traffic conditions. Ideally, the resulting driver behavior will be as similar as possible to the controlling mode of the system, assuming that the controller mode is optimal with respect to e.g. traffic throughput or comfort.

For the different functionalities of IRSA, we determined:

- whether a reaction is expected at all from the driver;
- whether this reaction is slower or quicker than without the system;
- what exactly is the reaction: e.g. braking or releasing the accelerator pedal, and if so, at what rate.

These driver reactions and the settings of the system (e.g. desired headway) have been derived from the first experiments with the system, and were complemented with estimations found in literature.

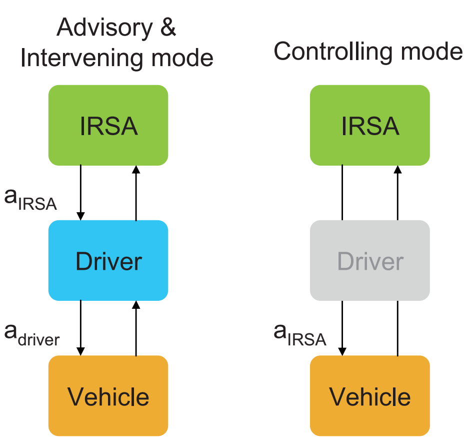

Fig. 3. Relation between advisory, intervening and controlling mode

V. RESULTS

A. Results for the Approaching a traffic jam scenario

The simulations with IRSA in a situation with congestion showed that the system has a positive impact on traffic flow. Vehicles slowed down earlier, having to brake less hard. The lane changing process at the lane drop appeared to benefit from this (although the IRSA system does not directly influence the lane changing behavior) and the congestion was reduced, with safety indicators staying at the same level or improving slightly.

Fig. 4 and 5 show the changes in total travel times and standard deviation of speed, for the different variants of IRSA experimented with, as compared to a reference case with no IRSA. The penetration rates were 100%, i.e. all vehicles were equipped with some form of IRSA. Also, the results for ACC (with no form of communication) were included.

Both the travel times and the variation in speed decrease (with the average speed increasing slightly), when the whole section is looked at. Just before the congested area, the variation in speed actually increases (as the equipped vehicles start braking at different times, depending on the difference in speed with the vehicles in the queue and how far away they are). On the whole, however, traffic appears to be more homogeneous, which is confirmed by a decrease in the variation in accelerations (by up to 40%). From this, it can be concluded that in this scenario, IRSA contributes to improved traffic safety and lower exhaust emissions. Delays (causing about 10% longer travel times in the reference case) are reduced by more than 30% for all CACC versions and by more than 20% for advisory IRSA.

The CACC2 version performs the best. The incorporation of information of the speeds of preceding –equipped- vehicles (at all times) helps to smoothen the traffic. The added value of messages from vehicles driving at speeds below 70% of the speed limit is clear for the (less efficient) CACC1 controller and for lower penetrations rates of the CACC2 controller. At a penetration rate of 100% CACC2, it appears that the information from the three predecessors alone is enough to reach the maximum impact.

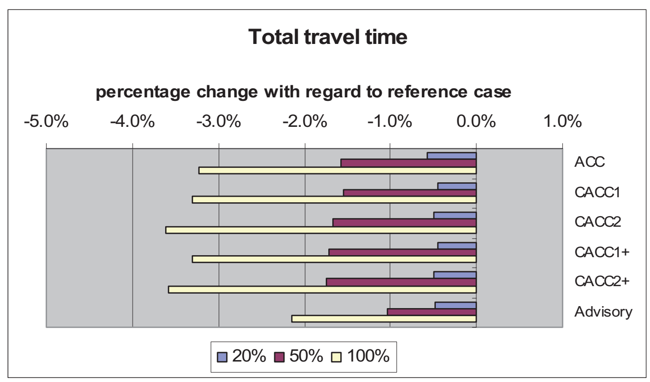

Fig. 4. Changes in total travel time, for different versions and penetration rates of IRSA in the Approaching a traffic jam scenario

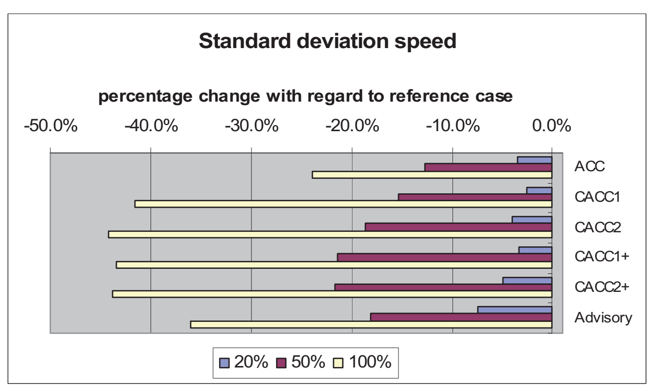

Fig. 5. Changes in the variation in speeds, for different versions of IRSA in the Approaching a traffic jam scenario

As can be seen in Fig. 6, the speed distribution changes, with higher average speeds at higher penetration rates. The distance and time headways between vehicles do not change much, because the IRSA system setting for headway is quite short (1 second). However, the times-to-collision decrease (as can be seen in Fig. 7), which means that the differences in speed between vehicles following each other are smaller than they are with no IRSA system – and traffic thus more homogeneous.

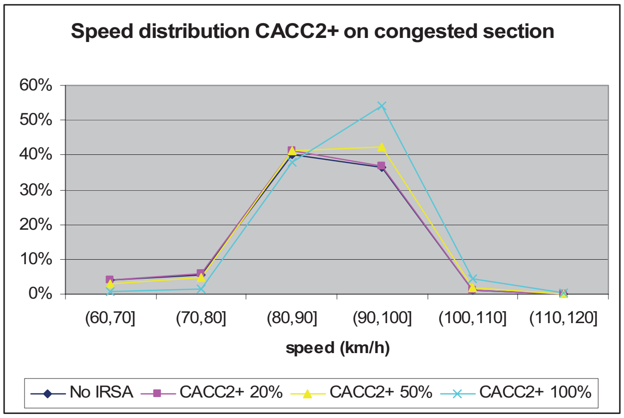

Fig. 6. Speed distributions for different penetration rates of CACC2+ in the Approaching a traffic jam scenario

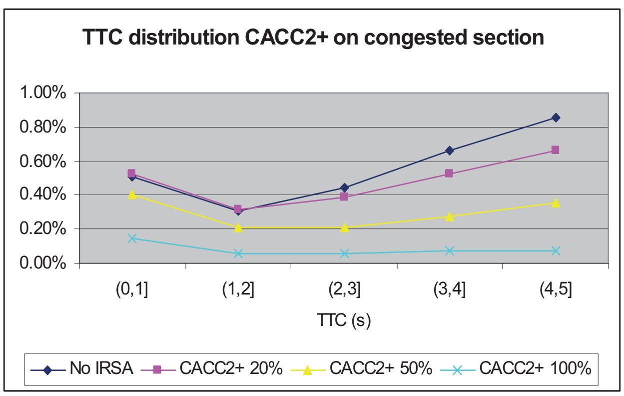

Fig. 7. Distribution of times-to-collision (small values only) for different penetration rates of CACC2+ in the Approaching a traffic jam scenario

B. *Results for the Approaching a reduced speed limit zone*

The vehicles equipped with IRSA are advised to slow down earlier than drivers of non-equipped vehicles usually would. Fig. 8 shows the speed profiles of non-equipped vehicles and vehicles equipped with the controlling mode of IRSA. It is clear that the equipped vehicles slow down much more smoothly.

When looking at the whole road network, no significant effects on throughput or safety are found. However, an important effect of IRSA in this scenario is that on the level of a cluster of vehicles the differences in speed become smaller, especially for higher penetration rates. At a 100% penetration rate, there are practically no small times-to-collision. The performance (with respect to safety indicators) improves with increasing penetration rates, and the controlling mode is, as expected, more effective than the advisory modes.

At lower penetration rates, especially for the controlling mode, the variation in speed in the area just before the reduced speed limit zone can be quite large. See for instance Fig. 9, which shows a speed distribution with two peaks. This effect can only be noticed with low penetration rates or when traffic is not too dense, since in dense traffic, the IRSA vehicles will force the normal vehicles to slow down in the same way.

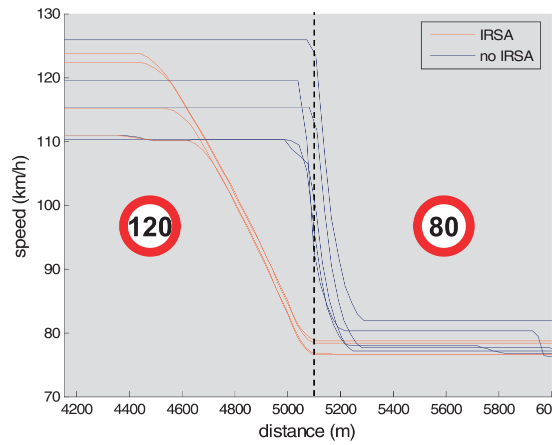

Fig. 8. Speed profiles of equipped and non-equipped vehicles in the Reduced speed limit scenario (controlling mode, 50% penetration rate)

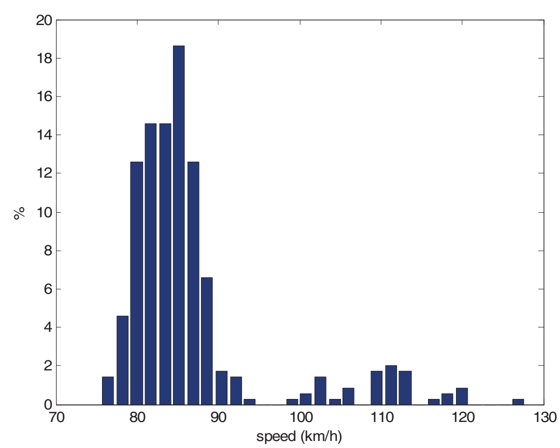

Fig. 9. Relative histogram of speeds of equipped and non-equipped vehicles in the Reduced speed limit scenario (150 m before the start of the lower speed limit, 5-minute interval, controlling mode, 50% penetration rate)

C. *Results for Leaving the head of a queue scenarios*

The results of this scenario show very clearly how different approaches and/or settings affect throughput and safety. The initial IRSA controller (CACC1) was somewhat ‘cautious’ compared to the reference case (see Fig. 10). This meant that the throughput (measured as the number of vehicles passing the intersection during the green time of a single cycle) was smaller than in the reference case which has been calibrated with values for accelerations found in practice. With the 'turbo' version of the IRSA controller the number of vehicles passing the intersection during green time was larger, which resulted in lower average travel times. The simple fixed headway controller had an improved throughput compared to the reference case, but less than IRSA turbo. This means that only keeping a fixed time headway does not optimize throughput when leaving the head of a queue. Since both controllers have the same headway setting of 1 second, it appears that a more complex, cooperative controller is needed to improve throughput. This proves the added value of the IRSA controller.

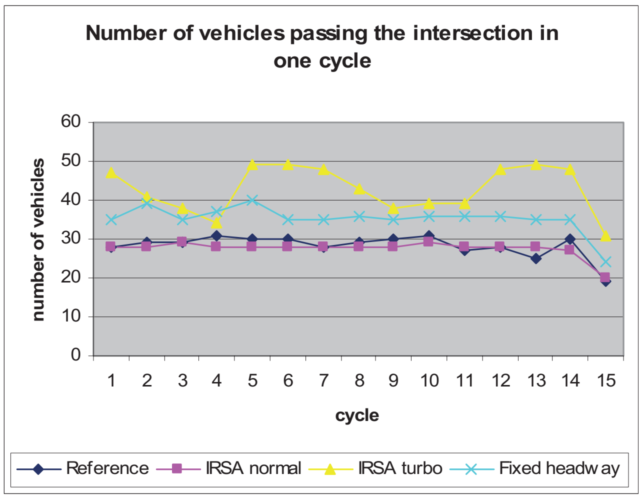

Fig. 10. Number of vehicles passing the intersection during one cycle in the Leaving the head of a queue scenario (100% penetration rate)

VI. Conclusion

The results presented here show some essential effects of IRSA in different scenarios. These results also show that IRSA has a wide range of effects, depending on the situation and settings of the system.

The main benefit of IRSA is that the distance to the predecessors can be maintained in a better way – safer, more comfortable or with a higher throughput, depending on the settings. The added value of communication is clear when comparing the IRSA CACC versions with just ACC. With the current settings, the extra communication in the Approaching a traffic jam scenario to slow down for the tail of the traffic jam, does not seem to add much.

The ITS modeller is a valuable tool in the assessment of a cooperative system like IRSA. It enables users to adapt vehicle and driver behavior, so that different algorithms and settings can be tried out easily. The changes in traffic patterns can be seen immediately in the traffic model's user interface. The output of completed runs can subsequently be used to assess the effects on traffic flows. Depending on the scenario, and the hypotheses tested, different indicators are used to assess the effects: from aggregated variables such as the average journey time and mean speed to disaggregated results, such as speed profiles. All these indicators together provide the full picture needed to assess cooperative systems, especially in dense traffic with many interactions between vehicles.

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