Simulation-based evaluation of I2V systems' impact on traffic performance: case study – COOPERS

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Abstract

In-vehicle technologies and cooperative services are attracting a lot of attention for their potential to deal with congestion problems and improve traffic safety. This paper aims to investigate the impact of infrastructure-to-vehicle cooperative systems, case of COOPERS, at the aggregate level, on traffic performance. A factorial experiment is designed with two factors: traffic demand and penetration of the system with three levels each. In total, nine scenarios are investigated. To replicate driving behavior with and without the system, speed distributions from a simulator experiment are used. A motorway section of 4 km is built in VISSIM simulation software. Indicators such as speed, density, delays and travel times are chosen to evaluate and compare the motorway performance with and without the system.

The results show that drivers driving with the system activated are more aware and alert to near future traffic conditions compared to driving without the system. Driving with the system activated is characterized by smoother and longer speed decelerations when approaching critical incident/accident events. The results show as well that the factors investigated significantly impact the motorway performance. Congestion reduces the impact of the system whereas higher penetration levels improve traffic operation on the motorway. Future research directions can include (1) investigating the impact of the system at the micro level such as lane changing or car-following behaviors; (2) levels of compliance with the system, which is an important aspect as well.
Keywords: cooperative systems, factorial experiment, micro simulation, traffic performance, driver simulator, driving behavior.

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1 Introduction

Nowadays, technology development has a remarkable impact on the driving task. Several systems exist which interact with drivers to assist them in the driving task. Furthermore, there are systems which interact with each other sharing traffic related information; these are known as Cooperative Systems. These systems include vehicle-to-vehicle (V2V), infrastructure-to-vehicle (I2V) and vehicle-to-infrastructure (V2I) communication systems which share information among the different parties involved. These systems are aimed to improve traffic performance and safety. COOPERS is based on I2V communication system and stands for "CO-OPerative SystEms for Intelligent Road Safety" which is a European Union Project. The goal of the project is to enhance road safety by direct and up to date traffic information communication between motorways' infrastructure and motorized vehicles.

Crucial aspects for I2V systems are the time interval it takes to share the information and the accuracy of the information. The information provision within COOPERS is 30 seconds. Information accuracy deals with exact detection of incidents/accidents on the motorway by road sensors i.e., detecting the start and the end of traffic events precisely. The system will be able to collect and share traffic information of several traffic events such as: accident–incident warnings (e.g. drivers are warned about an accident or incident ahead); weather condition warnings (e.g. drivers are made aware of environmental-related problems such as black ice, fog, heavy rain, or storms); roadwork and lane utilization information (e.g. drivers are made aware of the lane control policy applied and the lane utilization information); in-vehicle variable speed limit information; traffic congestion warnings and intelligent speed adaptation (Böhm *et al*. [1]).

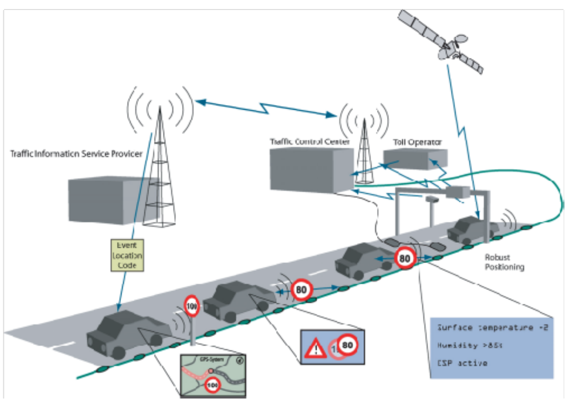

Figure 1: COOPERS continuous I2V communication along motorways [1].

In order to evaluate the system capabilities to improve traffic performance and safety, a driver simulator experiment and a field test experiment were

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conducted. Both experiments evaluated the impact of the system testing a single driver at a time interacting with other traffic. In other words, each participant drove the same test track twice, once with the system activated and once when it was inactive. Consequently; the results from both experiments reflect individual interactions (behavior of a single driver) with the environment. For instance; the driver simulator results (Hjort [2]), show that COOPERS System reduced stress levels and improved traffic safety by smoother speed reduction when facing critical driving situations. The results were drawn averaging the speed of all test drivers (total 48 drivers) with the system active versus inactive.

Similar outcomes were found when analyzing the field test experiment results by Farah *et al*. [3]. Again the results were drawn from the individual behavior of all participants (total 35 drivers) driving with and without the system. Drivers with the system active had on-average lower driving speeds when facing critical driving situations compared to when the system was not active. Drivers also maintained larger following gaps from the vehicle in front when driving with the system activated. Moreover; stress levels, expressed by heart rate variability, and distraction measured by tracking eye movements were lower when driving with the system. It is worth to notice that on the field experiments, the warning messages were fictitious i.e., participants received warning messages about oncoming events which actually did not take place on the motorway. Nonetheless, positive evidences were found that the system helps drivers to increase their alertness margins and awareness while approaching specific incident/accident traffic events when dynamic-real time warning messages are sent to them. However, these experiments did not examine the impact of the system at different traffic demand levels or at different penetration levels. As mentioned earlier, the results were drawn averaging the individual behavior of all drivers.

Cooperative Systems are still at development stages and are expensive to set up. Therefore, simulation tools are used to evaluate their impacts on traffic performance and safety. Some examples of the usefulness of simulation applied to the evaluation of Cooperative Systems are presented hereafter. Hoogendoorn and Minderhoud [4] conducted a study to evaluate the impact of Advanced Driver Assistance Systems (ADAS) in traffic performance and safety. They developed various scenarios considering different penetration and traffic demand levels using a simulation tool called "SIMONE" [5]. More specifically, Autonomous Intelligent Cruise Control (AICC) and Intelligent Speed Adaptation (ISA) were evaluated in a motorway setting. An experimental design with 2 factors was conducted with traffic demand and penetration levels as factors. Traffic demand was increased gradually and penetration levels were set up to 5%, 10%, 25%, 50% and 100%. The main scenario was a lane drop leading to a bottleneck event. Another study conducted by Hegeman *et al*. [6], evaluated the impact of an overtaking assistance system on traffic safety using a simulation tool called "RuTSim" [7]. Different penetration levels and threshold gaps for overtaking maneuvers were investigated. The software was used as well to investigate effects of longitudinal control driver assistance systems on rural roads. The impact of a Cooperative Variable Speed Limit System (VSLS) on traffic performance and safety was also evaluated by means of simulation (Grumert and Tapani [8]). An open source simulation tool called: "Simulation for Urban Mobility" (SUMO) was used. A simplified version of the E4 motorway in Stockholm was built and the VSLS implemented. Again the main scenario was a drop lane leading to bottleneck and shockwave conditions.

VISSIM [9] simulation tool has been used in a number of studies on Cooperative Systems. For instance, Nissan and Koutsopoulos [10] evaluated the impact of Variable Speed Limits (VSL) on motorway capacity and level of service. A case study was conducted on the E4 motorway in Stockholm. An advisory VSL System was evaluated before and after its implementation. Lee *et al*. [11] evaluated another VSL system in Virginia, U.S. on the Interstate Highway 495. They evaluated the operation performance by means of different compliance rates with the system and different traffic volumes. A drop lane scenario was recreated in the simulation tool in a 5-mile highway section. VISSIM was also used to evaluate the performance of a queuing warning system in a fictitious freeway (Pesti *et al*. [12]). Congestion was produced by work zone lane closures. Parameters chosen to evaluate the system were speed, aggregation interval, detector spacing and system location.

The use of simulation tools for the evaluation of Cooperative Systems has been demonstrated. Therefore, the objective of this study is to use VISSIM to analyze the impact of "COOPERS" at the aggregate level in terms of traffic demand and penetration levels, on traffic performance. The research motivation behind this analysis is to investigate aggregate driving behavior with and without the system in order to answer the question: what traffic demand and penetration level optimizes the traffic operation?

The rest of the paper is organized as following: Section 2 presents the simulator experiment and data collection, Section 3 introduces the assessment methodology and motorway design, Section 4 presents the results of the simulation and finally Section 5 presents the conclusions of the study and future research directions.

2 Simulator experiment and data collection

2.1 Driver simulator

The impact of COOPERS was evaluated in 2009 by the Swedish Transportation Institute (VTI) using a driver simulator. Driver simulator III was used, which is made of a real chassis car, which can make drivers experience movements in the three dimensions (x, y and z). The screen on which the imagery was displayed was a 120° horizontal field of view. The vehicle used was a SAAB 9-3 with 5 gears and 3 rear mirrors. Additionally, the messages from the system were presented on the on-board-unit (OBU) showing the incident type and the distance remaining.

2.2 Participant drivers

Forty-eight licensed drivers (24 males and 24 females) participated in the driver simulator experiment. These drivers were selected from a database maintained by VTI which advertised via local newspapers and its website. All drivers were required to fulfill the following conditions:

- Healthy drivers between 30 to 59 years old;
- Should not wear glasses;
- Drive at least 5000 km/year;
- Have held driving license for at least 5 years;
- Not having driving as a profession;
- Not being sensitive to car sickness.

The final sample of participants included test drivers between 28 and 59 years old, with a mean value of 42 years old. The range of the driving distance per year ranged between 5,000 and 40,000 with a mean of 19,500. Driving experience (driving license holding) ranged between 5 and 40 years with a mean of 22 years.

2.3 Messages and scenarios

The aim of the driver simulator study was to evaluate driving behavior under four different type of messages delivered to the participants hence four different scenarios were created. Each test driver drove the simulated road twice, once with the system activated and once when it was inactive. The road was a 40 km two-lane one-direction motorway with a speed limit of 110 Km/h. Traffic conditions on the road were set up as normal as possible with slower and faster moving cars which allows the test driver to overtake and be overtaken by other vehicles. The weather was set dry and a bit foggy. The simulator experiment set up (e.g. traffic and weather conditions) was similar for all drivers (see Table 1 for a further description of each message and scenario).

The following types of data were collected:

- Driver characteristics: age, gender, driving experience, etc.
- Driving behavior: speed, acceleration, braking force, side position, steering wheel angle, etc.
- State of the System: System “Active” or “Inactive”, message type, simulation time, simulation distance, event, case, etc.

For a complete description see [2].

3 Methodology

Previous studies found that test drivers behaved differently when the system was activated versus inactivated [1–3, 13, 14]. Specially, speed was reduced when facing critical driving events. To reflect those differences while approaching the incident, an imaginary motorway of 4 km was built into VISSIM simulation tool. The motorway was divided into several segments to account for different driving behaviors e.g., different speed distributions while approaching the incident. For

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Table 1: VTI simulator experiment (scenarios and messages).

Scenarios	Description	Message tested	Time for action
Ambulance	An ambulance approaches the driver at high speed from behind and needs to pass	Accident/incident warning	Intermediate
Fog	The driver has to pass a 1 km long section with heavy fog	Weather condition warning	Slow
Congestion	The driver approaches a sudden congestion that is standing still	Traffic congestion warning	Fast
Ghost driver	The driver meets a vehicle driving in the opposite direction in his/her lane on the motorway	Accident/incident warning	Very fast

each segment a speed distribution is identified based on the individual driving behavior of the 48 test drivers from the VTI simulator experiment. Furthermore, among the four scenarios tested, the "*fog*" scenario was chosen as the incident which best fits the objective of this study since the test driver in this scenario has no interaction with other vehicles [2]. Therefore, the fog scenario can be loaded with different traffic demand levels.

In order to simulate different penetration levels with and without the system, two classes of private cars were created (ON–OFF) based on their speed distribution at different segments along the fog scenario from the simulator experiment. Cars ON have the system active whereas cars OFF have the system inactive. Thus the percentage share of each class (ON–OFF) in the total flow is adjusted to reflect different penetration levels. Consequently, an experimental factorial design is defined in terms of traffic demand and penetration levels. Other simulation parameters are set to default values.

3.1 System active "cars ON"

The message was delivered 2 km in advance to the test drivers to allow them time to react to the oncoming event. Test drivers are able to see the fog at 0.5 km before it starts. The fog incident itself lasts for 1 km. Therefore, when the system is active, the 4 km motorway is divided into 5 sub-segments as follows:

(a) Sub-segment 1: lasts for 0.5 km to reflect a desired speed (no warnings, no events).
(b) Sub-segment 2: the next 0.5 km to reproduce the speed changes immediately after the message is delivered.
(c) Sub-segment 3: reflects the speed of the drivers knowing the oncoming event and approaching the fog incident and lasts for 1.5 km.
(d) Sub-segment 4: includes the 1 km fog incident and finally;
(e) Sub-segment 5: reflects how drivers try to regain their desired speed after the fog incident is terminated and last for 0.5 km.

The speed distribution for each sub-segment has been estimated based on the individual speeds of all 48 test drivers from the VTI "fog" scenario. Data collection points and speed decision points are also set up along the motorway. Collection points are set up at a frequency of 200 m along the motorway (20 points). Besides, 3 extra data collection points are defined as following: The first point is at exactly 0.5 km from the beginning of the motorway where test drivers receive the message and the second and third ones where the fog begins and ends. The scenario has in total 23 data collection points. Finally, speed decision points are set up at the beginning of each sub-segment. Figure 2 below depicts the segment configuration along the motorway.

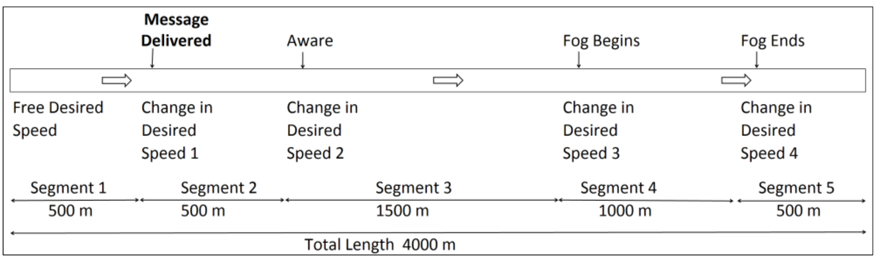

Figure 2: COOPERS "active" – segments.

3.2 System inactive "cars OFF"

When the system is inactive, no message is delivered thus the motorway is divided into four sub-segments as follows:
(a) Sub-segment 1: includes the first 2 km where drivers drive at desire speed.
(b) Sub-segment 2: reflects the speed changes immediately after the drivers can see the fog incident (0.5 km before the fog starts).
(c) Sub-segment 3: captures the speed within the fog itself and;
(d) Sub-segment 4: reflects drivers' speed after the fog incident is terminated, 0.5 km.

Therefore, four segments have been defined since drivers do not get any message about oncoming events and they only react when they can see the fog event. Data collection points are set up at a frequency of 200 m as well along the motorway (20 points). There is no message delivered thus the scenario has in

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total 22 data collection points. The most important points are 500 m before the fog incident where drivers can see the fog incident and where the fog begins and ends. Speed decision points are set up at the beginning of each sub-segment. Figure 3 shows the road segments configuration.

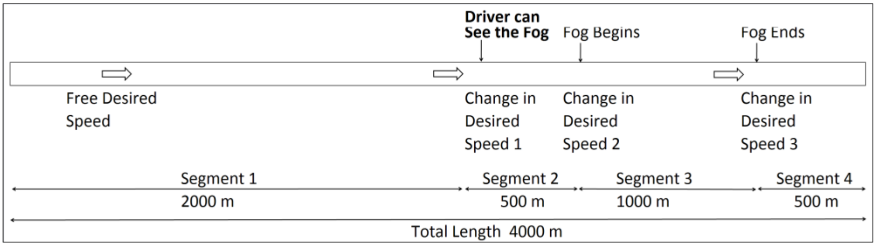

Figure 3: COOPERS “inactive” – segments.

3.3 Measures of performance (MOPs)

For evaluation purposes, two main indicators are selected as follows:

- Traffic speed (kilometers per hour, km/h);
- Traffic density (number of vehicles per kilometer per lane, veh/km/ln);

Speed and density are considered as main indicators for traffic performance at the aggregate level in this study. The performance of these indicators in the motorway is captured during the simulations by means of time-space graphs. Additionally, average delay and travel time are investigated in order to point out the optimum penetration level of the system.

3.4 Factorial experimental design

In the factorial experimental design two main factors are included as following: traffic demand and penetration level. Each factor is evaluated at three levels, resulting in nine scenarios. Demand level is the traffic flow rate in veh/h loaded in the motorway. The aim is to investigate how the system performs under different congestion regimes. Penetration level is the current share of the driver population driving with the system active. Therefore, the impact of the System on traffic performance and safety at different penetration levels and different traffic flow levels can be investigated. The resulting scenarios are described below in Table 2.

Table 2: Scenarios evaluated.

		Penetration level (%)		
		100%	**50%**	**0%**
Demand Level (veh/h)	**3600**	36A	36B	36C
	4200	42A	42B	42C
	4500	45A	45B	45C

3.5 Simulation set up

Since VISSIM is a stochastic simulation tool with a time-based step simulation process, the number of replications to estimate the indicators has been set to 10. The average results of the ten replications are used to evaluate the motorway traffic performance. The warm up period to fill up the network is set to 300 seconds.

4 Results

Time-space color graphs are used in order to present more comprehensive results since traffic conditions are dynamic over time and space. Color scales of 5-unit steps are applied to reflect traffic performance differences in speed and density on the motorway.

4.1 Speed

Figure 4 below depicts the speed results obtained from the simulations. As expected the highest speed is reached when the traffic demand is the lowest (scenarios 36A, 36B, 36C) since drivers are less constrained by vehicles in front of them, and can choose their speed more freely. Besides, the influence of the system at 100% penetration level is more obvious (scenario 36A) showing a more uniform speed in the first 0.5 km. The speed is reduced on average by 5–10 km/h after the message is delivered and the speed transition into the fog is smoother compared to more congested scenarios (42A–45A). Moreover; it can be seen that as the penetration level increases, a more uniform speed is achieved. For instance; at 0% penetration level (36C), drivers apply the braking pedal when they can see the fog incident thus the transition into the fog is more rushed (green areas near dark brown areas). Drivers reduce speed from 90–85 km/h to 55–50 km/h in a short distance (500 m) which is seen in the smaller yellow areas before the fog in scenario 36C compared to 36A scenario. At 50% penetration level (36B), there is mixed of green and yellow areas before the fog incident which is interpreted as a greater interaction among drivers (higher speed variability). In general at demand level of 3600 veh/h, speed is more harmonized (uniform) approaching the fog incident as penetration level increases (0, 50 and 100%).

At the demand level of 42 veh/h (scenarios 42A, 42B, 42C), the average speed at all penetration levels is lower compared to the previous demand which is expected since the motorway becomes more congested (smaller green areas). However, the impact of the system can still be observed at 100% penetration level e.g., after the message is delivered, the average speed is almost uniformly reduce over time and inside the fog the red area (45–40 km/h) is very small. When reaching the fog incident, it is still seen that the system still provides a smoother and longer transition into the fog. At 50% and 0% penetration levels, there is almost no difference in the average speed across time and space and the lowest speed is reached entirely inside the fog incident across time and space (big red areas) and the speed is unstable as drivers approach the fog.

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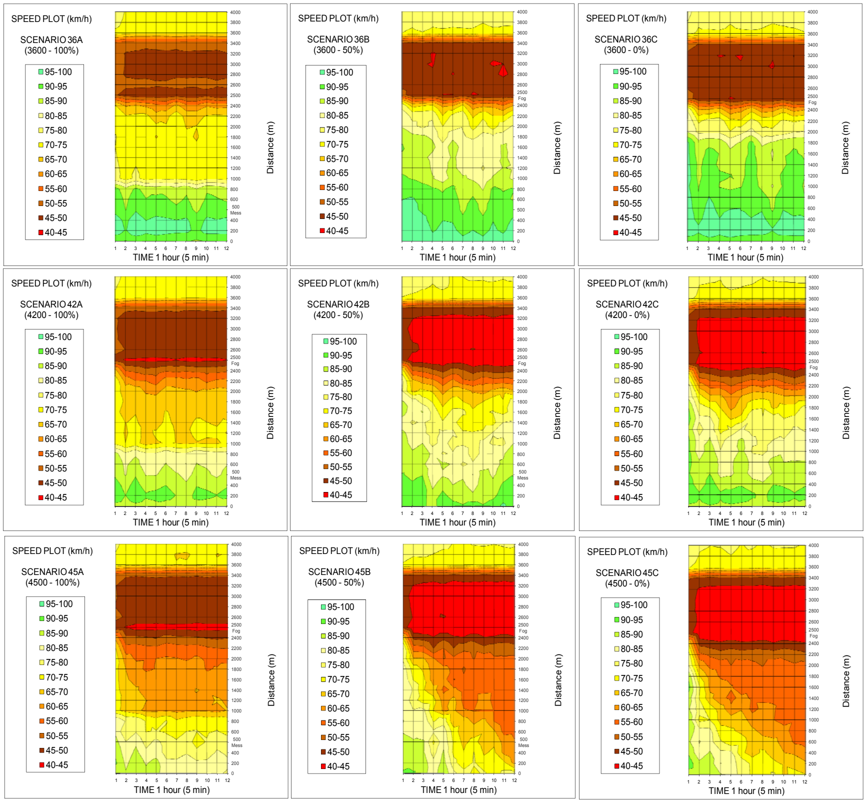

Figure 4: Speed pattern – all scenarios.

At 4500 veh/h (scenarios 45A, 45B, 45C), the impact of the system is drastically reduced; however, the system provides for better traffic performance (scenario 45A). For instance after the message, the speed is to some extend more stable over time and space (big bright brown areas) and drivers' speed approaching the fog is smoother and longer. Inside the fog, there is only a small red area where the fog starts. These results show the benefits of the system even with congested conditions. Whereas, at 50% and 0% penetration levels, it can be seen that congestion has totally absorbed any impact of the system. The speed is unstable over time and space. Inside the fog, the lowest is speed is reached (red areas 40–45 km/h) which dominates entirely in the fog incident over time and space.

From the analysis of the speed at different scenarios, the system at 100% penetration levels (scenarios 36A, 42A, 45A), provides a longer and smoother speed transition into the fog. Additionally, the highest speed is reached along the entire motorway on these scenarios, particularly; inside the fog (almost no red areas) since all drivers are warned in advanced and can adapt their speed.

However, the impact of the system is reduced as traffic flow increases which entail that the system brings in more benefits when drivers can adapt their speed, knowing about near future traffic incidents. At 50% penetration levels, (scenarios 36, 42B, 45B), drivers with the system active reduce their speed earlier while drivers without the system keep the same speed. Consequently, faster drivers (system inactive) will try to overtake the slower drivers (system active) which in fact can be observed in how the areas and colors are uneven over time and space in these scenarios. In other words, those drivers who get the information about oncoming traffic conditions will change their behavior (slow down) but at the same time, they become “obstacles” to drivers without the system. This entails high speed variability, increased driver interaction, leading to higher accident risk.

4.2 Density

Figure 5 below shows the time-space density plots for all scenarios. The lowest density is reached at scenarios 36A, 36B and 36C due to the lowest traffic demand levels. The system at 100% penetration (36A) provides the lowest average density (only green and yellow areas). It is also possible to see the impact of the message on the density. The density is 15–20 veh/km/ln before the message which rises to 20–25 veh/km/ln right after drivers receive the message. As penetration level decreases, (scenarios B, C), brown areas also start to appear inside the fog incident. For instance; the density is 35–40 veh/km/ln as drivers approach the fog which rises till 40–45 veh/km/ln inside the fog.

At scenarios 42A, 42B, 42C, the system in full penetration (scenarios A) provides a more stable density on the motorway compared to partial penetration (scenarios B and C). The impact of the message on the traffic density can still be observed as changing from green to yellow areas. Again the system provides for better performance as drivers approach the fog with lower and more stable densities. At 0% and 50% penetration levels, the density becomes higher and more irregular (bigger dark areas), especially, inside the fog.

When the motorway gets congested the impact of the system is reduced. We can see how the green areas have vanished at scenarios 45(ABC). Despite congestion, the system provides for better traffic performance (scenario 45A) with more stable densities over time and space. At lower penetration levels, scenario B and C, the density is much more unstable. Inside the fog, the highest density of all scenarios is reached (55–60 veh/km/ln) for about 30 minutes in a very short distance but the area of 50–55 veh/km/ln is larger and almost comes into view everywhere inside the fog incident. One explanation for this, as it was seen on the animations, is that vehicles start building up queues backwards just before the fog incident begins. The impact of the system is distorted in general. There is no clear sign of the message. An explanation of those crests or bubbles in the density is that there are platoons of vehicles with or without the system travelling together which may produce different density regimes along the network.

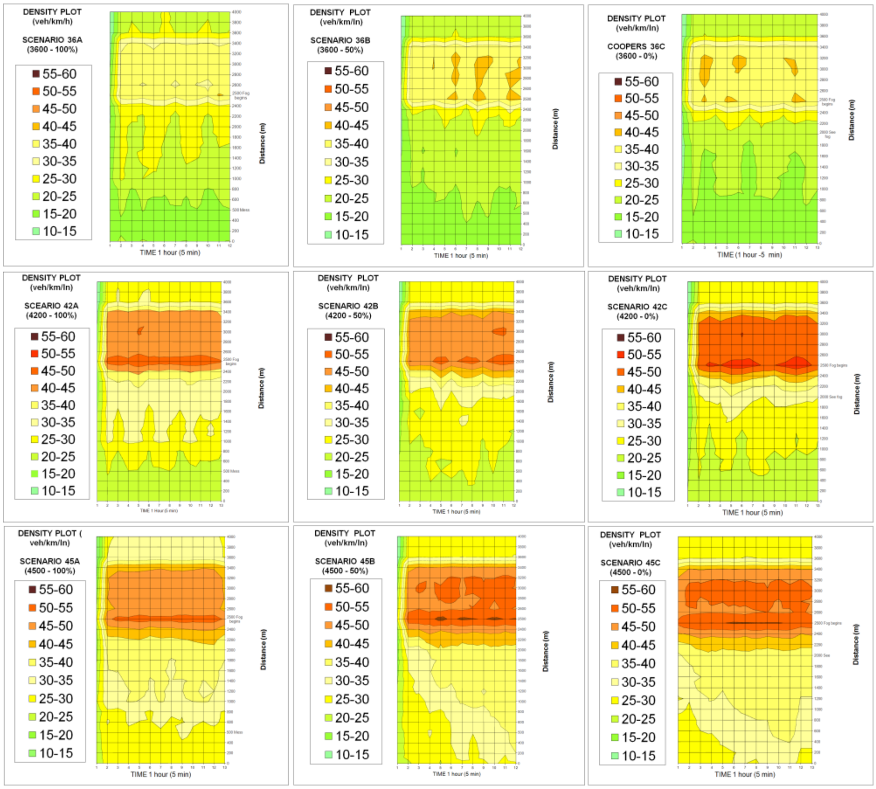

Figure 5: Density plots – all scenarios.

4.3 Optimum penetration level

From the results presented above, it was shown that the system at 100% penetration level provides smoother decelerations and lower densities over time and space. Meanwhile, other penetration levels (50%) have shown undesirable results on the traffic performance (higher speed variability and driver interaction). Therefore, extra scenarios are analyzed to get a sense of which penetration level performs the best on the motorway. Penetration levels at 25% and 75% are considered for evaluation looking at the average delay and average travel time on the motorway. Figure 6 below shows the simulation results. As expected, the higher the traffic demand levels, the higher the average delay and travel times. However, as the motorway becomes more congested, the penetration level of the system helps to reduce both indicators.

It is worth noticing that 25% penetration level provides for the longest travel time and the highest delay on the motorway especially at congested regimes (scenarios 45A, 45B, 45C). The highest values of the indicators were expected at the 0% penetration. However; the motorway performs better at 0% penetration level compared to the 25% scenario. These results entail that low penetration levels lead to lower traffic performance on the motorway even compared to the case where the system is not used at all.

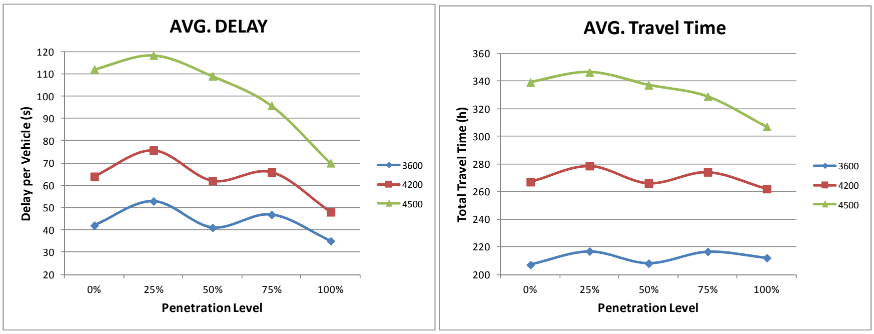

Figure 6: Average delay and travel time.

5 Conclusions and further research

This paper evaluated COOPERS System at an aggregate level with different traffic demand and different penetration levels. The fog scenario from the VTI simulator experiment was recreated in a motorway of 4 km built into VISSIM. Speed decision points and speed distributions of the individual test drivers were fed into the model to reflect different driving behaviors with the System active and inactive. The results are in line with what has been found for COOPERS in previous studies. In general, the system improves the traffic performance and safety on the motorway. For instance, knowing the near future fog incident, produces a speed adaptation which is longer and smoother. This behavioral adaptation produces a more homogeneous traffic operation when facing the critical incident. The change in speed and density is softened. The results show that traffic demand level is an important factor to consider when evaluating such cooperative systems. Congested regimes are likely to reduce or absorb the impact of the system since behavioral adaptation to the system becomes more difficult due to more limitations to freely choose speed on the motorway; however, the system still provides for better performance. Furthermore; the results suggest that full penetration level provides the best performance on the motorway compared to lower levels. Having some percent of the driving population with the system is likely to increase the interaction among drivers. This might lead to situations where drivers without the System (driving faster) will try to overtake drivers with the System (driving slower) which may lead to a higher traffic accident risk.

Finally, under all the conditions and assumptions made, there are positive evidences which lead to conclude that the system COOPERS if implemented for the whole driving population will help drivers to perform the driving task more carefully. Despite the promising results, this study had limitations that require

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further research. These limitations deal mostly with the data collected at the VTI simulator experiment. Even though driving simulators are calibrated and validated, there is always embedded an uncertainty on the results. Drivers may not behave or react in a simulator environment in the same way they would do in real world. Nonetheless, further studies need to be carried out to better understand the impact of the system e.g. compliance to the system is another important aspect of interest for further investigation. The impact of the system on risky drivers (young drivers) and drivers on risk (elderly drivers) is also of great importance for future research.

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