

# A Progressive Deployment Strategy for Cooperative Adaptive Cruise Control to Improve Traffic Dynamics

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**Abstract:** Cooperative adaptive cruise control (CACC) vehicles are intelligent vehicles that use vehicular ad hoc networks (VANETs) to share traffic information in real time. Previous studies have shown that CACC could have an impact on increasing highway capacities at high market penetration. Since reaching a high CACC market penetration level is not occurring in the near future, this study presents a progressive deployment approach that demonstrates to have a great potential of reducing traffic congestions at low CACC penetration levels. Using a previously developed microscopic traffic simulation model of a freeway with an on-ramp — created to induce perturbations and trigger stop-and-go traffic, the CACC system's effect on the traffic performance is studied. The results show significance and indicate the potential of CACC systems to improve traffic characteristics which can be used to reduce traffic congestion. The study shows that the impact of CACC is positive and not only limited to a high market penetration. By giving CACC vehicles priority access to high-occupancy vehicle (HOV) lanes, the highway capacity could be significantly improved with a CACC penetration as low as 20%.

**Keywords:** Intelligent transportation systems, telematics, vehicular adhoc networks, cooperative adaptive cruise control, traffic simulation, agent-based traffic simulation.

## 1 Introduction

During the last decades, the United States is constantly facing the problem of traffic congestion and its related negative effects pertaining to safety, loss of productivity, wear and tear on vehicles and many others. The expectations of the use of telematics to solve this problem are high, since this technology has shown a possibility of increasing the highway capacity and the safety if widely adopted<sup>[1]</sup>

An intelligent transportation systems (ITS) system that is gaining popularity is cooperative adaptive cruise control (CACC). CACC vehicles are intelligent vehicles that have the ability of sharing traffic information via vehicular ad hoc networks (VANETs) or wireless technology as well as regular radars (refer to Fig. 1). CACC is a new and further development of the adaptive cruise control (ACC) technology by having faster and more accurate real time information sharing among the equipped vehicles. Research has shown that CACC has a potential of improving the traffic dynamics (flow, density, speed variation, average speed, etc.) and safety if widely adopted (related literature covered in the next section). However, reaching a high CACC market penetration level is not occurring in the near future. In addition, the literature pertaining to the impact of CACC on traffic dynamics is lacking because the technology is still fairly new (no CACC equipped vehicles exist in the market at this point).

In order to address this topic, the CACC systems have to be explored thoroughly by studying how the drivers use the systems, how the equipped vehicles communicate and interact with each other, and most importantly, how the CACC systems impact certain traffic performance metrics at low penetration levels. Thus, this

study presents a progressive deployment approach that demonstrates how CACC could have a positive impact on traffic dynamics with penetration levels as low as 20%.

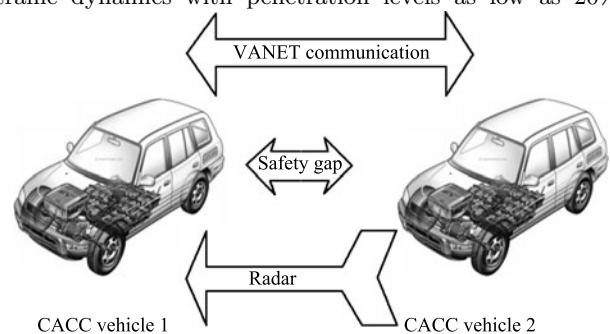


Fig. 1 CACC vehicle-to-vehicle communication using VANETs and radar

## 2 Review of the literature

ACC is a technology intended for the driver's comfort and safety but could have an impact on the overall traffic flow. References [2–4] studied the effects of ACC on the traffic performance concluding that the effect of ACC could be positive and negative at the same time. According to [5], ACC has no impact on the traffic performance if the level of ACC-equipped vehicles is low. The minimum time gap that can be achieved by ACC vehicles is 0.8 seconds<sup>[6]</sup>. Reference [2] concluded in their study that with a relatively high penetration of ACC (more than 60% penetration), and even under the most advantageous conditions, the ACC system can only have a slight impact on highway capacity and performance.

Unlike ACC, the literature on CACC systems is still very premature. There are still no CACC design standards on

how the technology operates. Thus, one area of research focuses on creating CACC designs frameworks, aiming to standardize and optimize the use of the technology. Several studies like [7–10] examined CACC designs and architectures, but most of the studies did not explore the traffic flow effects of CACC quantitatively in terms of throughput, capacity, and congestion reduction.

As it is expected in the near future that many (or most) of the vehicles will be fully automated, [11] studied a way to optimize the movements of the CACC vehicles through intersections to avoid collisions and minimize intersection delays.

One of the very few studies that targeted this paper’s area of research was [2], which identified that CACC vehicles enable closer vehicle following (time gap as low as 0.5 s) and concluded that the CACC technology has the potential to significantly increase the highway capacity — potentially doubling the capacity at a high market penetration. Another important finding of this study is that the capacity effect is very sensitive to the market penetration based on the fact that the reduced time gaps are only achievable between pairs of vehicles that are equipped with the CACC technology. However, the study simulated only a single-lane (meaning no overtaking is possible between vehicles). Even more, the study did not have trucks implemented in the model which could have a major effect on creating shock-waves on the freeway. Another equally important study was [1], which focused on the impact of CACC equipped vehicles on the traffic flow performance. The study revealed that CACC indeed shows a potential positive impact on the traffic throughput. In addition, CACC seems to increase highway capacity near a lane drop (bottleneck scenario). Furthermore, the impact of a dedicated CACC lane (i.e., a lane strictly operated by CACC-equipped vehicles) was studied, and it was shown that with a low CACC penetration (< 40%), the effect might lead to a degradation of traffic performance. Although the contribution of both studies<sup>[1, 2]</sup> were beneficial to the CACC literature, both studies did not take into account modeling a CACC special lane that allows manual non-CACC vehicles to operate on. We believe that this approach could have a potential in using the advantage of CACC equipped vehicles being grouped together, without wasting lane capacity like in the case of having a CACC dedicated lane, under low CACC market penetration levels.

A stability analysis of a macroscopic simulation model conducted by [12] showed that the CACC system improves the dynamic equilibrium capacity over the ACC system. In a different study, [13] explored the effect of CACC on traffic dynamics on a multilane freeway (with the existence of a ramp) and showed that CACC indeed has a positive impact proportional to the CACC market penetration and the density of the traffic. The simulation model used in that study along with the proposed CACC algorithms were thoroughly discussed and validated in a separate study by [14]. Another study by [15] showed the effect of CACC to annul stop-and-go traffic in different traffic conditions. All these studies agreed that there is a need for a progressive deployment strategy for CACC since at penetration levels lower than 40% CACC, no significant impact was observed

on the traffic flow.

### 3 Simulation model details

In order to study the impact of CACC on the traffic dynamics (particularly on traffic flow, average speed, and travel time spent), microscopic simulation is a suitable approach to study the individual behavior of every equipped vehicle (agent) and predict their overall impact on the whole system. Thus, a stochastic microscopic traffic simulation model F.A.S.T. (flexible agent-based simulator of traffic) was developed.

The object-oriented model developed using Java®, is an expansion of a preexisting open-source microscopic model originally developed by [16]. Some of the most important additions to the original model are: increasing the highway distance from 2.5 km to 6 km, adding two additional lanes (F.A.S.T. has 4-lanes), collecting microscopic properties as well as macroscopic properties, and most importantly modeling the behavior of CACC vehicles, with or without a priority access to high-occupancy vehicle (HOV) lanes referred to in this study as special HOV lanes (i.e., CACC accessible HOV lanes). Furthermore, additional randomness is added to the original model by manipulating the key variables of the car-following models and making them more stochastic. Note that Treiber’s study focused on the ACC systems and their impact on the highway capacity while this study focuses on the CACC systems and their impact on traffic performance.

F.A.S.T. consists of a 6 km U-shaped freeway having four lanes, where ongoing traffic flows counterclockwise (shown in Fig. 2). Vehicles enter the system at different speeds and at a user-specified arrival rate, and exit after traveling the 6 km distance. There are two types of agents in F.A.S.T.: cars and trucks. The standard dimension of cars (whether CACC equipped or not) is  $4 \times 2 \text{ m}^2$  and for trucks is  $6 \times 2 \text{ m}^2$  (considering mid-sized trucks only).

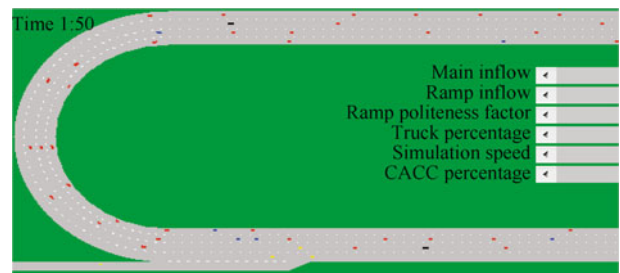


Fig. 2 Snapshot of the Java-based simulation model F.A.S.T

In order to generate a sufficient speed perturbation to our model, an on-ramp is added to the model, where the entering agents (all manual vehicles) may come to a full stop if there is not enough gap for them to enter the lane adjacent to the ramp. The 200 meters long ramp serves as a generator of perturbations that impact the traffic performance negatively by creating inhomogeneity in the speeds of the operating agents. A constant arrival rate of 500 veh/h will be entering the freeway from the on-ramp. The red agents are the non-CACC equipped vehicles, the black agents are the trucks, the yellow agents are the vehicles flowing from

the ramp, and the blue agents are the CACC equipped vehicles.

Finally, all the vehicles in F.A.S.T. (CACC and manual) have different desired maximum speeds decided randomly following a uniform distribution between 100 and 120 km/h for cars, and between 90 and 110 km/h for trucks, considering that the speed limit imposed on the highway studied is 100 km/h ( $\approx 60$  mph). Drivers tend to go at increasing speeds whenever the roadway geometric characteristics are fine, regardless of the posted speed limit<sup>[17]</sup>. The algorithms used in F.A.S.T. were explained and validated in a previous study<sup>[14]</sup>. Note that in CACC, the driver retains full control of the vehicle at all times.

## 4 Model validity

In order to verify and validate the calibration of the proposed traffic model, the traffic data generated by the model was compared to historical data taken from the *Highway Capacity Manual* (HCM). According to the HCM, at a speed limit of 60 mph, the average flow rate in a multilane highway is around 2200 veh/h/ln (refer to Table 1).

Table 1 Flow rate according to speed limits (source: *Highway Capacity Manual*, December 2000)

Speed limit (mph)	Flow rate (veh/h/ln)
60	2200
55	2100
50	2000
45	1900

The model was simulated at an arrival rate of 8500 vehicles/h (for four lanes) having only manual vehicles operating on the 6 km highway with a speed limit of 60 mph (or 100 km/h).

There were no trucks, no CACC vehicles, and no vehicles flowing from the on-ramp. Note that vehicles tend to go over the speed limit following a uniform distribution between 100 km/h and 120 km/h.

It was observed that 8500 veh/h was the highest achievable arrival rate in order to keep a steady flow of traffic. After running the simulation model for 30 replications, 90 minutes each, the average flow rate of the simulation was 8425.20 veh/h (per four lanes) equivalent to 2106.3 veh/h/ln. This is a very close flow rate to the one obtained from the HCM.

Another way of validating the proposed model was to compare the speed-flow curve for multilane highway sections according to historical data taken from the HCM. Fig. 3 shows the speed-flow relation at different speeds. The free-flow speed — the speed that a driver would travel if there were no congestion or other adverse conditions ahead, tends to be stable until the flow rate reaches a specific level where it starts dropping.

A similar pattern was observed in the proposed model after running simulations with increasing arrival rates until reaching 8500 veh/h (or 2125 veh/h/ln) and taking a snapshot of the output at a time without any congestion. Fig. 4 shows the speed-flow curve generated from the proposed

model (scattered line) compared to the HCM curve (solid line).

The curves in Fig. 4 (compared to Fig. 3) are very similar in behavior and follow the same pattern. As observed, after reaching a certain maximum capacity, the speed starts to drop.

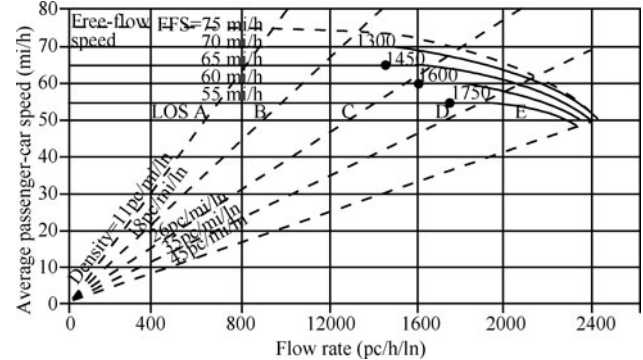


Fig. 3 Speed-flow curves for multilane highway sections (source: *Highway Capacity Manual*, December 2000, Exhibit 21-3, pp. 21-4)

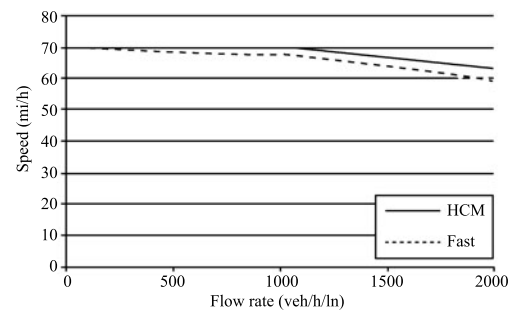


Fig. 4 Speed-flow curves in the simulation model

## 5 Simulation experiments and results

The traffic simulation F.A.S.T. was used to examine the significance of the impact of CACC on the traffic dynamics and particularly on the traffic flow, the average speed and the travel time spent.

### 5.1 Simulation setup

Following the previous literature about ACC and CACC designs<sup>[9, 18, 19]</sup> and the algorithms from [14], the time-gap setting of the CACC is set to 0.5 s if following a CACC vehicle. In other words, when both vehicles are CACC equipped, their time gap setting is set to 0.5 s where both vehicles are connected via wireless communication. When a CACC equipped vehicle is following a truck or a non-CACC equipped vehicle, the time gap is set to a headway gap uniformly distributed between 0.8 s (younger/aggressive drivers) and 1.0 s (older/considerate drivers) — acting in the same manner as an ACC vehicle and relying only on its radar but without establishing any wireless communication. In the case of a non-CACC vehicle (i.e., manual) following another CACC vehicle or non-CACC vehicle following another non-CACC vehicle (no wireless communication is established; no radar), the time gap setting is between 1.0 s and 1.8 s (uniform distribution)

which is a commonly observed headway gap reported in previous studies<sup>[20–22]</sup>.

For traffic generation, a previously user defined incoming traffic is divided randomly between the four lanes. A high traffic scenario (saturated/oversaturated) can lead to congestion on the freeway, while a low traffic scenario (under saturated) can result in a free flow of vehicles. The base case (initial state of the system), is having no CACC equipped vehicles operating with an arrival traffic rate of 4000 veh/h (on four lanes). The penetration rate of CACC systems varied between 0% CACC and 20% CACC. The arrival rate varied between five scenarios: 4000 veh/h, 5000 veh/h, 6000 veh/h, 7000 veh/h, and 8000 veh/h. The percentage of trucks in the system is fixed at 10%. The 4000 veh/h and 5000 veh/h were considered a low traffic density scenario (no traffic jams but with some oscillations observed resulting from the ramp) while the other scenarios had more congestions especially the 7000 veh/h and the 8000 veh/h (where severe traffic jams were observed). At 6000 veh/h, a stop-and-go traffic is observed with minor traffic congestion occurrences. The model was run for warm-up periods of five minutes in every replication as the system is initially empty (no vehicles/agents on the highway). From the observation of the model animation as well as the output, 5 minutes is sufficient to reach conditions that are typical of normal running traffic conditions in order to obtain more accurate results.

Since previous studies (refer to the literature review section) have already showed that CACC has indeed a significant positive impact on the traffic dynamics at high market penetration levels ( $> 40\%$  CACC), the experiments conducted in this paper relaxed that constraint by limiting the number of CACC penetration to 20% and giving the CACC vehicles priority access to special HOV lanes.

The simulation model was extended allowing CACC equipped vehicles to operate solely on special lanes or more accurately special HOV lanes. This approach enables the researchers to study the effect of a low CACC penetration rate on the traffic dynamics by giving CACC vehicles priority access to special lanes, in this case HOV lanes, allowing the CACC vehicles to operate closer to each other. This is an initial stage before a higher penetration level of CACC is reached (i.e., market penetration of 40% or more) where the CACC vehicles could be scattered on all the lanes and still improve the traffic performance. A small percentage of 10% manual vehicles were allowed to use the special HOV lanes considering that those vehicles have two or more passengers onboard. In addition, CACC equipped vehicles are initially created on the special HOV lane that we will refer to as lane 3. Fig. 5 shows the different lanes with their relative numbers. CACC vehicles do not change lanes at any part or time in the system.

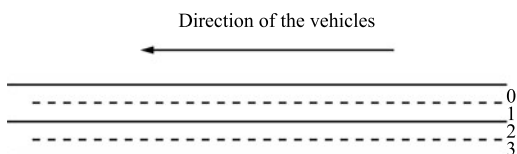


Fig. 5 Different lanes in the simulation model grouped by number

Vehicles that are not CACC equipped are uniformly created on the four lanes in the system. However, lane 3 has a much smaller ratio of non-CACC to CACC than the other lanes because 20% of the overall vehicles are CACC equipped and are located on lane 3. In addition, non-CACC equipped vehicles that are initialized on lanes 0, 1, or 2 are allowed to switch lanes to lane 3 but only on a 10% probability (i.e., 10% of the non-CACC vehicles are allowed to switch the special HOV lane). Non-CACC equipped vehicles operating on lane 3 are allowed to change lanes to other lanes only if their incentive criterion was met (refer to the MOBIL lane change model by [23]). Trucks are allowed to operate on HOV lanes following the same rules that impact the non-CACC equipped cars. A snapshot taken in this phase is shown in Fig. 6 where the formation of platoons (groups of blue CACC vehicles) on the special HOV lane is observed.

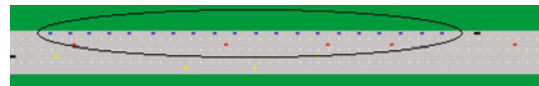


Fig. 6 Snapshot of F.A.S.T. with special HOV lanes

A comparison was made between scenarios of low CACC penetration levels of 20% with priority access to the special HOV lanes (referred to as 20% CACC HOV scenario), scenarios without CACC vehicles operating on the highways (without special lanes; referred to as 0% CACC), and scenarios with 20% CACC scattered on all the lanes without any special lanes (referred to as 20% CACC scattered). Section 5.2 covered these experiments with a ramp creating perturbations in the traffic flow. Section 5.3 covered the same experiments but without the ramp, having the same three scenarios in comparison (0% CACC vs. 20% CACC HOV vs. 20% CACC scattered). Higher arrival rates of 7000 veh/h, 8000 veh/h, 9000 veh/h, and 10000 veh/h were modeled in the scenario without a ramp.

The vehicles were allowed to overtake and weave. All the experiments had the same previous base assumptions:

- 1) Good weather (no rain, snow, fog, etc.).
- 2) Good pavement conditions.
- 3) No impediments to traffic flow.

4) Accidents and failures in the operation of the sensors and communication of CACC design equipment were not taken into consideration.

## 5.2 Experiments with a ramp

To ensure statistical validity, 30 stochastically independent simulations were performed for each selected scenario. Having a total of 15 scenarios (three different penetration rates and five different arrival rates), the simulations were run for 90 minutes per each replication. A constant arrival rate of 500 veh/h was set for the vehicles entering the freeway from the on-ramp to create perturbations in the traffic flow. Three performance metrics were collected and analyzed: traffic flow rate, average speed of the vehicles, and the travel time spent. The flow rate was collected by getting the throughput of the agents passing through two fixed points located at 100 meters before the ramp. The average speed (time mean speed) was collected by averaging the speed of all the agents passing through a fixed point

located at 100 meters before the ramp acting as a loop detector. The travel time spent was collected by averaging the total time spent by every agent in the system (time of exit minus time of entry).

### 5.2.1 Flow rate analysis (with ramp)

Fig. 7 shows the rate of flow in different scenarios comparing 20% CACC penetration operating on special HOV lanes, 20% CACC scattered on all the lanes, and the base case of 0% CACC penetration.

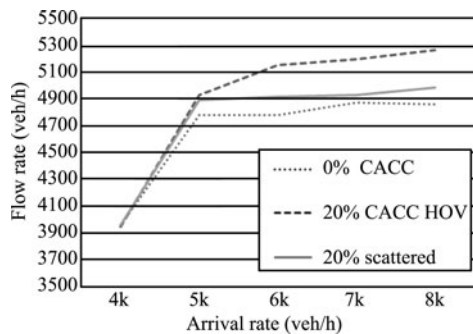


Fig. 7 Flow rate analysis (with ramp)

Observing Fig. 7, the scenario of 20% CACC HOV shows superiority over the other cases with a traffic flow rate proportional to the increasing arrival rate of the vehicles. Since the flow rate in all the three scenarios compared was somehow close, ANOVA test was conducted to identify the statistical significance of CACC in the different scenarios studied, followed by Dunnett T3 Post hoc analysis to find relations and patterns among the different scenarios. For the 4000 veh/h arrival rate scenario, ANOVA showed no significance between all the three scenarios. In the 5000 veh/h scenario, significance was found in both 20% CACC penetration (scattered and HOV cases) compared to the base case of 0% CACC. However, the Dunnett T3 test showed no significance between the two 20% CACC penetration scenarios resulting in a  $p > 0.05$ . At 6000 veh/h, a statistical significance between the two 20% CACC penetration scenarios was observed (showing the superiority of the HOV scenario). In the 7000 veh/h scenario, no significance was found between the base case of no CACC penetration and the 20% CACC scattered scenario. However, the 20% CACC HOV outperformed the base case scenario significantly. In the 8000 veh/h scenario, the behavior was somewhat similar to the previous case of 7000 veh/h where the 20% CACC HOV scenario outperformed the two other scenarios significantly, demonstrating the superiority of the 20% CACC HOV scenario over the other scenarios.

Thus, the results confirmed that placing the CACC vehicles on special HOV lanes, at a low market penetration of 20%, has a statistically significant positive effect on the traffic flow. This effect is highly observed when the traffic is saturated (i.e., arrival rate of 6000 veh/h and more) because at free-flow conditions, all the scenarios have a free-flow traffic that is able to reach the maximum capacity of the freeway.

### 5.2.2 Time spent analysis (with ramp)

Additionally, in Fig. 8, a comparison of the average time spent in the system by the vehicles was collected. The three

cases of 0% CACC, 20% CACC scattered, and 20% CACC HOV were compared.

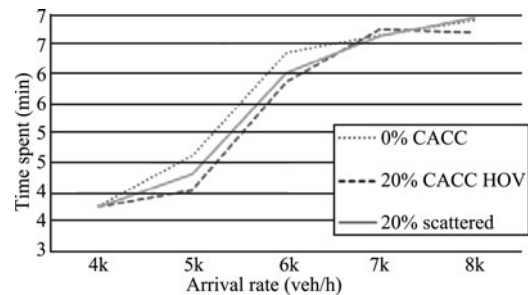


Fig. 8 Travel time spent analysis (with ramp)

An S-shape function was observed with no direct relation between the CACC penetration level and the time spent at 4000 veh/h arrival rate. ANOVA was conducted resulting in  $\text{Sig} = 0.531$  (showing that the difference is not statistically significant). At 5000 veh/h arrival rate, the 20% CACC scattered had a slight significance compared to the 0% CACC ( $p = 0.049$ ). The 20% CACC HOV showed statistical significance compared to the base case ( $p = 0.00$ ) and the difference between the 20% CACC scattered and the 20% CACC HOV was statistically significant. In the 6000 veh/h arrival rate, both scenarios with the 20% CACC outperformed the base case significantly, but the difference between them (scattered vs. HOV) was not statistically significant. At 7000 veh/h and 8000 veh/h, ANOVA showed no significance in the results ( $\text{Sig} = 0.709$  for the 7000 veh/h and  $\text{Sig} = 0.454$  for the 8000 veh/h). Thus, it is concluded that with the presence of a ramp, the 20% CACC HOV scenario performed slightly better than the two other scenarios where vehicles spent less time in the system at low to medium arrival rates (lower than 7000 veh/h). At high arrival rates, the results were somehow similar (no statistical difference) between the three scenarios studied. However, this does not mean that the 20% CACC HOV performed poorly. Since the flow rate increases proportional to the increasing arrival rate, and with a decreasing average speed<sup>1</sup> in the 20% CACC HOV (explained thoroughly in Section 5.2.3), this proves that the density is increasing (from the simple traffic flow formula  $q = k \times v$ . If  $q$  or flow is increasing and  $v$  or speed is decreasing,  $k$  has to be increasing). Therefore, the density in the 20% CACC HOV is higher than the density of the other scenarios (in which the flow was lower and the next section shows that the average speed was higher). Thus, with a higher density, it would not be accurate to compare the travel time spent between the scenarios as the densities are completely different.

### 5.2.3 Average speed analysis (with ramp)

The impact of CACC on the highway average speed in the three scenarios: 20% CACC scattered, 20% CACC HOV, and 0% CACC, was analyzed using one-way ANOVA. Fig. 9

<sup>1</sup>Note that although the traffic flow formula used applies only to the space mean speed (and not the time mean speed we are using in this study), the time mean speed is always higher than the space mean speed. Therefore the space mean speed will follow the same decreasing behavior as the time mean speed validating the assumption made.

shows the average speed at different arrival rates of vehicles. At 4000 veh/h, the results of ANOVA did not show any statistical significance ( $p = 0.185$ ) between the means of the three scenarios.

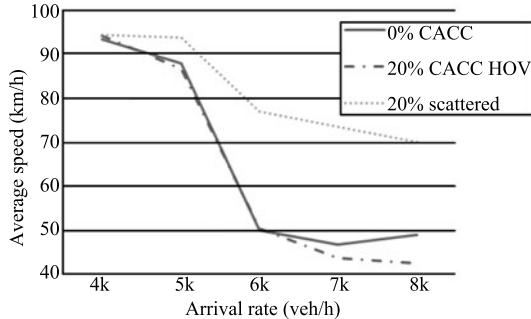


Fig. 9 Average speed analysis (with ramp)

At 5000 veh/h, the results were not significant between the 20% CACC HOV and the 0% CACC base case. However, statistical significance was found between the 20% CACC scattered scenario and the base case. Also, statistical significance was found between the 20% CACC scattered scenario and the 20% CACC HOV scenario, showing that the 20% CACC scattered case had a higher average speed. At 6000 veh/h, 7000 veh/h, and 8000 veh/h, the results followed the same behavior. When comparing the 20% CACC HOV scenario with the base case, no statistical significance was found. When comparing the 20% CACC HOV scenario with the 20% CACC scattered scenario, statistical significance was found where the 20% CACC scattered scenario resulted in superior average speed. In the case of 20% CACC HOV, the average speed collected was lower than the other two cases studied. However, the flow in this case outperformed the other two cases. The reason for the lower average speed in the 20% CACC HOV scenario is that at a higher arrival rate and with sufficient CACC penetration, the speed is being divided among the operating vehicles (CACC and non-CACC equipped). This shows that the accelerations and decelerations of the vehicles became smaller resulting in a smoother flow of traffic because the CACC vehicles (that are supposed to reduce the standard deviation of the speed) are placed only on one lane — lane 3, out of four available lanes. Thus, the reduction of speed was due to a slower but steady traffic where traffic jams did not occur. This results in a higher rate of flow and a lower overall average speed. A study by [24] explored such behavior by studying the effects of an on-ramp on the traffic flow. The study suggested an explanation for this hysteretic effect — effect of a system that has a memory is not felt at the same instant. Reference [24] simulated freeways with on-ramps with a fluid-dynamic traffic model and explained how the average vehicle speed will adapt to an equilibrium speed, which monotonically decreases with the growing density of the traffic.

### 5.3 Experiments without a ramp

In this phase, experiments were without an on-ramp to model the effect of “natural” shockwaves (shockwaves resulting only from vehicles’ decelerations) on traffic perfor-

mance without the impact of vehicles flowing from an on-ramp creating perturbations in the flow. The same three performance metrics from Section 5.2 were used (and collected in the same way). In these experiments, higher arrival rates were chosen because of the absence of the on-ramp that plays a major role in creating perturbations that ultimately leads to traffic congestions. The arrival rates of 7000 veh/h and 8000 veh/h are cases where no traffic congestions occurred (low traffic hours). The arrival rates of 9000 veh/h and 10000 veh/h are cases where traffic congestions were observed (high traffic hours).

#### 5.3.1 Flow rate analysis (without a ramp)

Fig. 10 shows the rate of flow between the three different cases studied and different arrival rates.

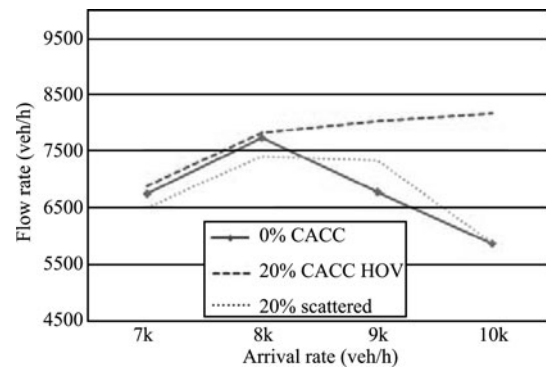


Fig. 10 Flow rate analysis (without a ramp)

As observed in Fig. 10, the more vehicles arrive to the system, the flow increases until reaching a critical point where it starts declining. At 0% CACC the critical point is at 8000 veh/h where after that point the flow starts degrading. Note that when validating the model, the arrival rate of 8500 veh/h was the critical point before the flow started to degrade. However, the difference here is that trucks were added. Trucks create perturbations to the traffic and reduce the rate of flow by adding more perturbations to it. At 20% CACC scattered, the flow rate was slightly better where after 8000 veh/h, the flow rate stayed constant until 9000 veh/h; but then at 10000 veh/h, it degraded. At 20% CACC HOV, the flow rate kept increasing exponentially beyond the critical point of 8000 veh/h and even beyond the highest arrival rate of 10000 veh/h.

To confirm the stated observations, one-way ANOVA test followed by Dunnett T3 post hoc tests were conducted to evaluate the difference between the three cases studied. At 7000 veh/h, there was no statistical significance between 0% CACC and 20% CACC HOV. There was a slight statistical significance between 0% CACC and 20% CACC scattered where the flow of 0% CACC was higher. At 8000 veh/h, a slightly different behavior was observed. There was no statistical significance between the 0% CACC and 20% CACC HOV cases, nor between the 0% CACC and 20% CACC scattered. Statistical significance was found between 20% CACC HOV and 20% CACC scattered. This shows that in low traffic densities, the effect of CACC is minimal and most of the time non-significant. Note that in the previous two scenarios, no congestion was detected. At 9000 veh/h, there was an improvement observed between the 0% CACC

case and the 20% CACC scattered case. However, the improvement was not statistically significant. On the other hand, the improvement between the 0% CACC base case and the 20% CACC HOV case was significant (with  $p = 0$ ). Note that in this case, some congestions were observed but not in all the replications. Finally, at 10000 veh/h arrival rate, congestions occurred at some point in all the cases. Less congestion was observed in the 20% CACC HOV. There was no significance between 0% CACC and 20% CACC scattered cases. However, there was a statistical significance between the base case of 0% CACC and the case of 20% CACC HOV that showed a major improvement in the flow rate.

It is concluded from the results that the CACC increases the highway capacity even at low penetration levels if placed on special HOV lanes. However, this effect is highly dependent on the arrival rate of the vehicles. It is extremely important here to mention that the system reaches its maximum capacity in the 0% CACC scenario and the 20% CACC scattered scenario which was around 8000 veh/h (per four lanes) at the moderate arrival rate scenario of 8000 veh/h. However, the more we increased the arrival rate above that limit to 9000 veh/h and 10000 veh/h, the queues of the vehicles stretched until reaching the system's entrance and no additional agents were able to enter the system. As this shows the definitive superiority of the 20% CACC HOV scenario, the ANOVA comparisons conducted at these conditions are not considered very accurate because at 9000 veh/h and 10000 veh/h, the system was oversaturated and no agents were entering the system resulting in extenuating a deadlock that was ignored in the analysis.

### 5.3.2 Time spent analysis (without a ramp)

Additionally, in Fig. 11, a comparison of the average time spent in the system by the vehicles was collected. The same three cases of 0% CACC, 20% CACC scattered on all the lanes, and 20% CACC operating solely on the special HOV lanes were compared.

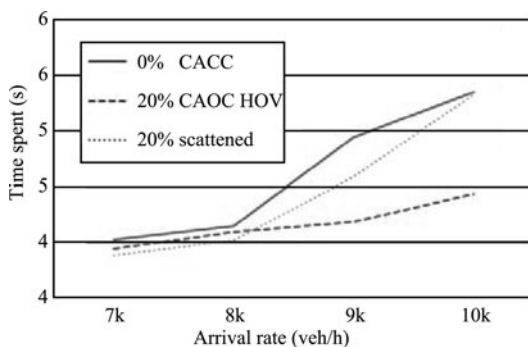


Fig. 11 Time spent analysis (without a ramp)

The difference in the results is observed at arrival rates higher than 8000 veh/h where the 0% CACC vehicles took longer to travel through the system, and the 20% CACC HOV vehicles evidently performed better than the other two cases. To validate these observations, ANOVA was conducted. At 7000 veh/h, the difference between the 20% CACC HOV and the two other scenarios was not significant. At 8000 veh/h, ANOVA showed also no statistical significance. At 9000 veh/h no significance was observed between

the 20% CACC scattered and the base case. The results of the 20% CACC HOV showed statistical significance and outperformed the two other scenarios. The exact same behavior was observed at a 10000 veh/h arrival rate, showing the positive impact of CACC in reducing the travel time for the vehicles but only in high arrival rates when traffic is saturated.

### 5.3.3 Average speed analysis (without a ramp)

The average speed was also analyzed. The 20% CACC HOV showed an overall better performance than the other two cases as shown in Fig. 12.

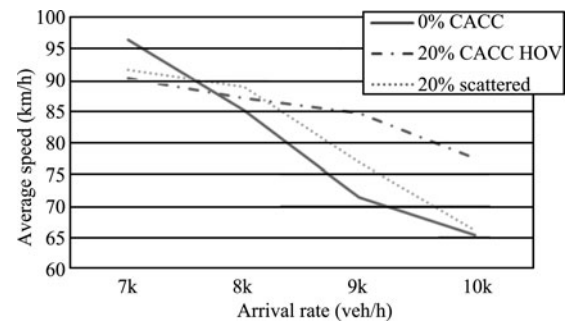


Fig. 12 Average speed analysis (without a ramp)

ANOVA test was conducted to evaluate the significance of the results and compare the three different cases correctly. In the 7000 veh/h and 8000 veh/h (low traffic hours), ANOVA showed no statistical significance between the results of the three cases studied. At 9000 veh/h, significance has been found between 0% CACC and 20% CACC HOV case and between 20% CACC HOV and 20% CACC scattered. The results showed that the 20% CACC HOV outperformed the other cases. Although the results of the 20% CACC scattered looked better than the 0% CACC base case, the improvement was not statistically significant. At 10000 veh/h, the behavior was similar to the previous scenario. There was no significance between the 0% CACC base case and the 20% CACC scattered case. On the other hand, the 20% CACC HOV performed better than both scenarios with statistical significance. This validates the previous claim that at higher arrival rates, a low percentage of CACC equipped vehicles placed on special HOV lanes have a significant positive impact on the average speed. However, the CACC impact is highly dependent on the arrival rates of the vehicles.

It is worth mentioning that in Section 5.2.3, the average speed was lower although the flow was higher because of the hysteretic effects of the on-ramp that was present at that phase. The on-ramp played a major role in reducing the speed to an equilibrium speed that decreases inversely proportional to the growing density as explained in a study by<sup>[24]</sup>. In this phase, this effect was not observed because the on-ramp was not present.

## 6 Conclusions

In this paper, F.A.S.T, a microscopic traffic simulator that simulates the effect of cooperative adaptive cruise control (CACC) equipped vehicles on a four-lane freeway, was

used to identify the impact of CACC on traffic dynamics in low CACC market penetration. CACC vehicles are not available in the car market at this point. It is assumed that their spreading will grow in the future. Since reaching a high CACC penetration level is not occurring in the near future, this study presented a progressive deployment approach that demonstrated to have a great potential of reducing traffic congestions at low CACC penetration levels by placing CACC vehicles on HOV lanes until reaching a 40% CACC penetration level. At 40% CACC and higher, previous related studies<sup>[1, 2, 13]</sup> showed the positive significance of CACC by simply scattering the vehicles on all the lanes of the freeway.

## 7 Discussion and future work

The public acceptability of the CACC technology is a major challenge facing the CACC studies. A study by [25] showed that most of the people would not feel comfortable driving at a headway gap of 0.5s and considered it to be too close to the preceding vehicle. With the driver retaining full control of the vehicle at all times, we believe that the public acceptance of the CACC technology will only be a temporary challenge solved by its increasing usage and design standardization, just like any new breakthrough technology.

Perhaps the most important improvement needed in the proposed model, is for it to be extended to allow accidents to occur and to implement other obstacles on the roads (a blocked lane to create a bottleneck for example), forcing the vehicles to merge into a smaller number of lanes. Additional scenarios could be added to explore the impacts of CACC on the traffic dynamics more efficiently. Up to now, the CACC platoons once formed do not deal with the size of the platoons and the possibility of a vehicle attempting to join/exit the platoon (to take an exit for instance). Platooning algorithms could be explored and mixed with the existing CACC algorithm, in order to avoid possible problems resulting from inefficient platooning practices.

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