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Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp

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Abstract:

Purpose: In this paper, the impact of Cooperative Adaptive Cruise Control (CACC) systems on traffic performance is examined using microscopic agent-based simulation. Using a developed traffic simulation model of a freeway with an on-ramp - created to induce perturbations and to trigger stop-and-go traffic, the CACC system's effect on the traffic performance is studied. The previously proposed traffic simulation model is extended and validated.

By embedding CACC vehicles in different penetration levels, the results show significance and indicate the potential of CACC systems to improve traffic characteristics and therefore can be used to reduce traffic congestion. The study shows that the impact of CACC is positive but is highly dependent on the CACC market penetration. The flow rate of the traffic using CACC is proportional to the market penetration rate of CACC equipped vehicles and the density of the traffic.

Design/methodology/approach: This paper uses microscopic simulation experiments followed by a quantitative statistical analysis. Simulation enables researchers manipulating the system variables to straightforwardly predict the outcome on the overall system, giving researchers the unique opportunity to interfere and make improvements to performance. Thus with simulation, changes to variables that might require excessive time, or be unfeasible to carry on real systems, are often completed within seconds.

Findings: The findings of this paper are summarized as follow:

- Provide and validate a platform (agent-based microscopic traffic simulator) in which any CACC algorithm (current or future) may be evaluated.

- Provide detailed analysis associated with implementation of CACC vehicles on freeways.

- Investigate whether embedding CACC vehicles on freeways has a significant positive impact or not.

Research limitations/implications: The main limitation of this research is that it has been conducted solely in a computer laboratory. Laboratory experiments and/or simulations provide a controlled setting, well suited for preliminary testing and calibrating of the input variables. However, laboratory testing is by no means sufficient for the entire methodology validation. It must be complemented by fundamental field testing. As far as the simulation model limitations, accidents, weather conditions, and obstacles in the roads were not taken into consideration. Failures in the operation of the sensors and communication of CACC design equipment were also not considered. Additionally, the special HOV lanes were limited to manual vehicles and CACC vehicles. Emergency vehicles, buses, motorcycles, and other type of vehicles were not considered in this dissertation. Finally, it is worthy to note that the human factor is far more sophisticated, hard to predict, and flexible to be exactly modeled in a traffic simulation model perfectly. Some human behavior could occur in real life that the simulation model proposed would fail to model.

Practical implications: A high percentage of CACC market penetration is not occurring in the near future. Thus, reaching a high penetration will always be a challenge for this type of research. The public accessibility for such a technology will always be a major practical challenge. With such a small headway safety gap, even if the technology was practically proven to be efficient and safe, having the public to accept it and feel comfortable in using it will always be a challenge facing the success of the CACC technology.

Originality/value: The literature on the impact of CACC on traffic dynamics is limited. In addition, no previous work has proposed an open-source microscopic traffic simulator where different CACC algorithms could be easily used and tested. We believe that the proposed model is more realistic than other traffic models, and is one of the very first models to model the behavior
CACC vehicles on freeways.

Keywords: intelligent transportation systems, vehicular ad hoc networks, cooperative adaptive cruise control, traffic simulation, agent-based traffic simulation

1 Context and problem statement

Building more roads and highways is no longer a feasible solution to reduce traffic congestion, a problem that has countless consequences. As expanding the infrastructure is often not practicable, due to the great expense and because most of the major traffic cities have already reached their maximum capacity for roads and highways, and with the ongoing advancement of artificial intelligence and wireless technology, the emphasis has turned to telematics technology integrated with Advanced Driver Assistance Systems (ADAS). The interest in ADAS applications has been expanding since the early nineties as a tool for making traffic more efficient and safer. ADAS technology functions by reducing (or supporting) the dependence on the human aspect in the driving task. Examples of such systems are: collision avoidance system, automatic parking, traffic sign recognition, driver drowsiness detection, lane departure warning system, and blind spot detection.

Adaptive Cruise Control (ACC) is an ADAS system introduced by General Motors in 1990 that is similar to conventional cruise control in that it attempts to maintain the cruise speed initially set by the driver in the addition of the equipped vehicle maintaining a proper safe distance with the predecessor vehicle. As shown in (figure 1), using a forward-looking radar (or laser/Lidar setup) installed behind the front grill of the vehicle, the ACC equipped vehicle (the vehicle on the right in this case) has the ability of detecting the speed and distance of the predecessor vehicle or any other obstacle ahead. Thus, if the predecessor vehicle decelerates, the braking system of the ACC vehicle is signaled to decelerate. If the predecessor vehicle accelerates again, the engine is signaled to accelerate, limited by the initial cruise control maximum desired speed set initially by the driver.

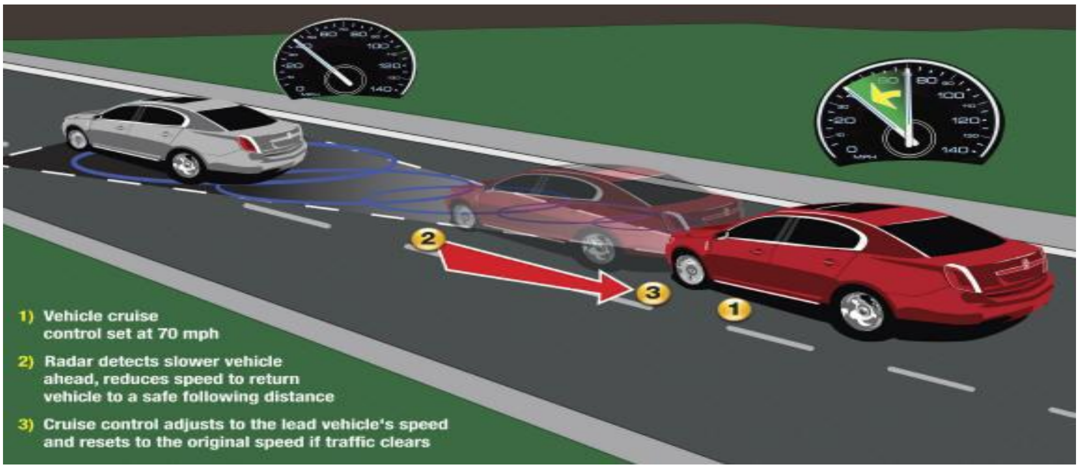

Figure 1. Adaptive Cruise Control system (Prabs, 2010)

ACC system has several operational disadvantages. For instance, an ACC equipped vehicle has a limited deceleration range and its ACC system cannot be used at very high or low speeds (Arem et al., 2003).

With a constant demand for traffic information on the surrounding traffic conditions and with the recent developments of vehicle-to-vehicle communication via Vehicular Ad-hoc Networks (VANETs), a recent potential of vehicles sharing traffic information to tackle traffic congestion and impact the traffic dynamics positively started to appear. Wireless communication via VANETs has been adopted due to the great advantages offered by the technology allowing high mobility, efficiency, and also being economically feasible. Cooperative Adaptive Cruise Control (CACC) is a more advanced technology providing the equipped vehicles with more accurate information about the preceding vehicle through speedy and real-time vehicle-to-vehicle traffic data sharing among CACC equipped vehicles. The effect of CACC on the traffic flow and safety is still vague due to the deficiency of research in this area.

Therefore, this research was oriented towards intelligent transportation systems (ITS) and particularly focused on CACC systems, and their effect on traffic dynamics. The latter's growing popularity is still premature. Most of the CACC related literature defines designs and frameworks of the CACC technology, but fail to focus on the overall impact of CACC systems on the traffic characteristics (Arnaout & Bowling, 2010).

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. This paper addresses the issue of modeling traffic flow and speed with CACC vehicles running on a freeway. The paper will analyze results of different simulations, and compare them to other related studies previously conducted.

2 Background of the study

Several studies like (Shladover, 2009), (Girard et al., 2001), (Bruin et al., 2004), and (Misener et al., 2002) 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. One of the few papers that studied the effect of CACC on traffic performance was (VanderWerf et al., 2003). The study showed that the CACC system leads to drastic improvement in the traffic efficiency and increase the lane flow from 2100 veh/hr/ln on a 100% manual highway to 2900 veh/hr/ln on a 20% manual, 20% ACC and 60% CACC equipped highway. However, the model used in this study did not contain any trucks (that play a major role in creating traffic oscillations) and did not allow overtaking (lane changing play a major role in inducing decelerations to the flow of traffic) since only a single lane was modeled. Another study was (Arem, et al., 2006), which focused on the effect of CACC equipped vehicles on the overall 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. The impact of a dedicated CACC lane (i.e. a lane strictly operated by CACC-equipped vehicles) was also studied, and it was shown that with a low CACC penetration (< 40%), the effect will lead to a degradation of traffic performance. The study only focused on the shockwaves and the average speed as performance metrics and did not consider other essential macroscopic measures such as the traffic flow of rate.

In the first study (Arnaout & Bowling, 2010), the effect of CACC was explored on a multilane freeway without any external perturbation generators (no obstacles, no ramp, to blocked lanes, etc) having a speed limit of 100 km/hr. The impact of CACC was assessed by collecting data of several performance measures such as the flow, the average speed, and the standard deviation. At the end of the study, it was concluded that the CACC systems can contribute to a more stable traffic flow and also increasing the capacity especially in high density traffic hours. Also, the study confirmed previous findings (VanderWerf et al., 2003; Arem et al., 2006) that the impact of CACC is highly dependent (and proportional) on the CACC market penetration. However, the simulation model used in that study was simplistic as most of the key variables used were static (i.e. fixed speeds for all the vehicles, fixed headway gap, etc).

In this study, in the analysis of the CACC impact on the traffic flow and the average speed an on-ramp is introduced to create additional perturbations and trigger the stop-and-go effect that ultimately leads to traffic congestion. To model this situation, the simulation model used in the first study (Arnaout & Bowling, 2010) was expanded to include an on-ramp, and also by adding more randomness to the model by turning most of the static variables into random variables (making the model more realistic).

3 Microscopic traffic simulation

Microscopic traffic simulators are the ideal simulation tools to realistically reproduce the individual flow of vehicles (microscopic) resulting in the collective flow of traffic (macroscopic). Agent-based microscopic traffic simulation was used in this study because it allows capturing emergent phenomena and accurately studying the impact of CACC and ITS on traffic systems.

3.1 Traffic simulation

In a previous study (Arnaout et al., 2010), a microscopic traffic simulator was proposed, F.A.S.T. (Flexible Agent-based Simulator of Traffic), that models the interaction of intelligent CACC equipped vehicles on a freeway. In that study, the simulation model F.A.S.T. and its related CACC algorithms used was introduced but only the algorithms were verified and validated (the model validation is covered in section 3.2). The agent-based microscopic simulation model F.A.S.T. uses the Intelligent Driver Model (IDM) developed by (Treiber et al., 2000) as the car-following model, and the Minimizing Overall Braking Induced by Lane change (MOBIL) developed by (Kesting et al., 2007) as the lane changing (or overtaking) model. The two car models used (IDM and MOBIL) were previously validated and are widely used in traffic simulation studies. In this paper, F.A.S.T. consists of a 6 km U-shaped highway having four lanes, where ongoing traffic flows counterclockwise shown in (Figure 2). Vehicles (or agents) enter the system at a user-specified arrival rate, and exit after traveling the 6 km distance. Another way for the vehicles to enter the system is by using the on-ramp. A constant arrival rate of 500 veh/hr enter the freeway from the on-ramp. The 200 meters long ramp plays a major role in inducing perturbations to the traffic flow that leads to traffic inhomogeneity and ultimately to traffic congestion. 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 x 2 meters and for trucks is 6 x 2 meters. In F.A.S.T., trucks cannot be CACC equipped. The range of longitudinal detection of CACC frontal radar (also referred to as the headway range) is 120 meters (Bazzan & Klügl, 2009) and the Dedicated Short Range Communication (DSRC) wireless range is 300 meters (Olariu & Weigle, 2009). A warm-up period of 5 minutes was used to reduce inconsistencies in the data collection by waiting for the system to become steady before collecting the traffic data.

The simulation model runs under the following base conditions:

- good weather
- good pavement conditions
- no impediments to traffic flow

In addition, accidents and failures in the operation of the sensors and communication of CACC design equipment are not taken into consideration.

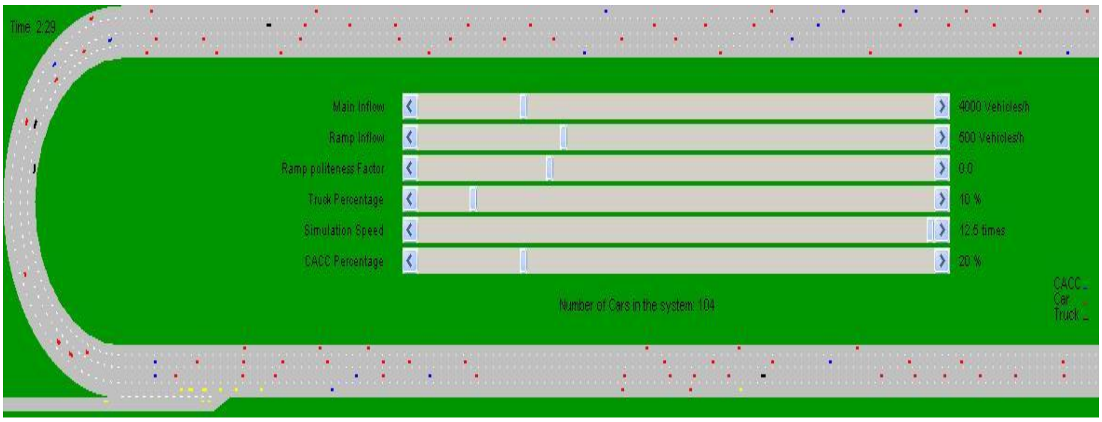

Figure 2. Snapshot of the simulation model F.A.S.T.

F.A.S.T. and its related CACC algorithms are completely open-source and can be used and downloaded from http://www.georgearnaout.com under F.A.S.T.

3.2 Model validation

In order to verify and validate the proposed traffic model, the traffic data generated by the model was compared to historical data taken from the Highway Capacity Manual (Council, 2000). According to the Highway Capacity Manual, at a speed limit of 60 mph (≈ 100 km/hr), the average flow rate in a multilane highway is around 2200 veh/hr/ln (refer to table 1).

Speed Limit = 60 mph (or 96.56 km/hr)	Flow rate = 2200 veh/hr/ln
Speed Limit = 55 mph (or 88.51 km/hr)	Flow rate = 2100 veh/hr/ln
Speed Limit = 50 mph (or 80.46 km/hr)	Flow rate = 2000 veh/hr/ln
Speed Limit = 45 mph (or 72/42 km/hr)	Flow rate = 1900 veh/hr/ln

Table 1. Flow Rate according to speed limits (The Highway Capacity Manual, 2000)

The model was simulated at an arrival rate of 8500 veh/hr (for four lanes) having only manual vehicles operating on the 6 km highway with a speed limit 60 mph. 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/hr and 120 km/hr. Drivers tend to go at increasing speeds whenever the roadway geometric characteristics are fine, regardless of the posted speed limit (Garber & Gadirau, 1988). It was observed that 8500 veh/hr 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/hr (per four lanes) equivalent to 2106.3 veh/hr/ln. This is a very close flow rate to the one obtained from the Highway Capacity Manual (2200 veh/hr/ln).

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 Highway Capacity Manual. (Figure 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.

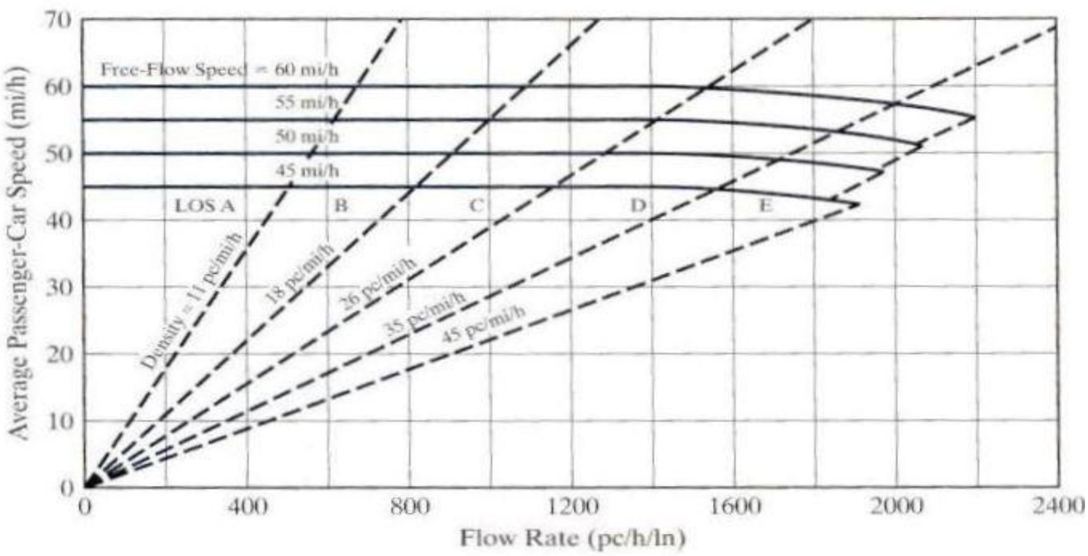

Figure 3. Speed-Flow Curves for multilane highway sections (The Highway Capacity Manual, 2000, Exhibit 21-3, 21-4)

A similar behavior was observed in the proposed model after running simulations at different arrival rates: 2000, 3000, 4000, 5000, 6000, 7000, 8000 and 8500 veh/hr. Thirty replications of each arrival rate were conducted. (Figure 4) shows the speed-flow curve generated from the proposed model.

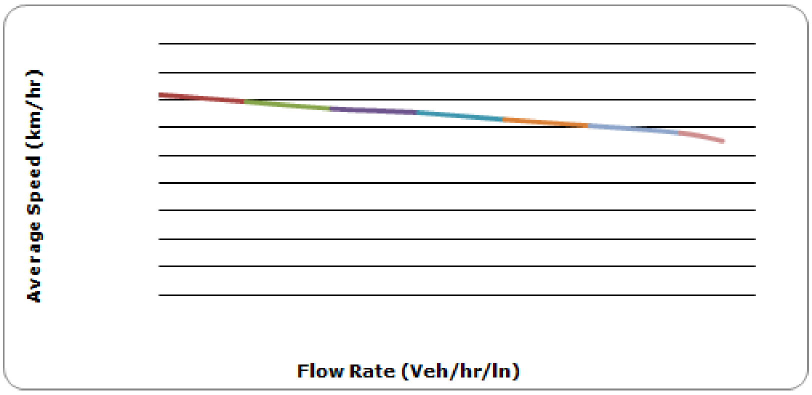

Figure 4. Speed-Flow Curves in the simulation model

The curve in both (figure 3) and (figure 4) are very similar in behavior. As observed, the speed increases until reaching a certain maximum capacity and after that it starts dropping. Note that after the maximum capacity is reached, as the average speed is dropping the flow rate starts dropping too in a behavior similar to the one shown in figure 5.

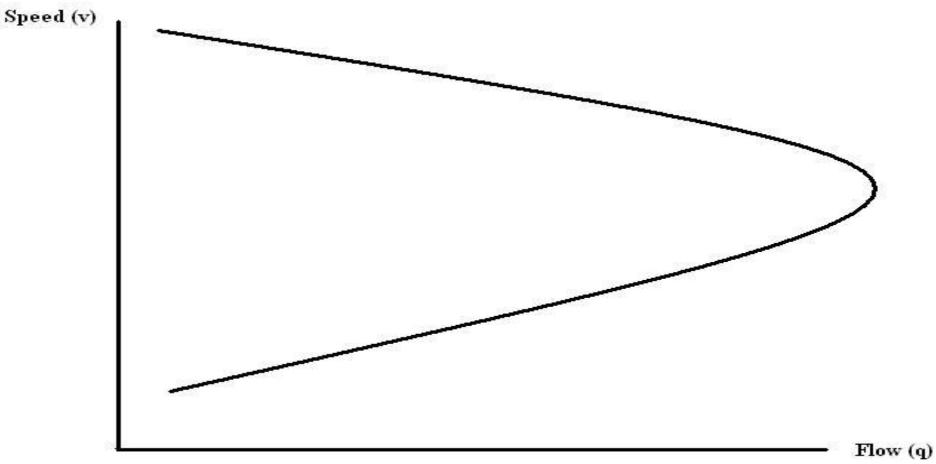

Figure 5. Speed - flow relationship (The Highway Capacity Manual)

4 Experiments and evaluation

Following the previous literature about ACC and CACC designs (Bruin et al., 2004; Naus et al., 2010; Kesting et al., 2007), and the algorithm described in our previous work (Arnaout et al., 2010), the time-gap setting of the CACC is set to 0.5 seconds if following a CACC vehicle. When following a truck or a non-CACC equipped car, the time gap is set to a headway gap uniformly distributed between 0.8s (younger/aggressive drivers) and 1.0s (older/considerate drivers). For traffic generation, a previously user defined incoming traffic is divided randomly between the four lanes. A high traffic scenario can lead to congestion on the freeway, while a low traffic scenario can result in a free flow of vehicles. The default case (initial state of the system), is having no CACC equipped vehicles operating with an arrival traffic rate of 4000 veh/hour (on four lanes). The penetration rate of CACC systems varied between multiple scenarios in multiples of 20%. The arrival rate varied between five scenarios respectively: 4000 veh/hr, 5000 veh/hr, 6000 veh/hr, 7000 veh/hr, and 8000 veh/hr. The percentage of trucks is fixed at 10%. The experiments were divided into two phases:

4.1 Experiments and analysis with a ramp

With the same initial configuration, an on-ramp has been added to the system in order to create perturbations and provoke stop-and-go traffic. The upstream propagating waves result in flow inhomogeneity that have a significant impact on creating congestion and reducing traffic flow. A constant arrival rate of 500 veh/hr was set for the vehicles entering the freeway from the on-ramp. (Figure 2) shows a snapshot of the model with the ramp vehicles flowing onto the free way. The vehicles wait at the ramp for an appropriate safe spacing (to avoid collisions) and merge into the freeway. Their entrance induces perturbations as the other preceding vehicles are forced to decelerate in order to avoid a collision with the entering vehicles (yellow agents).

Two performance metrics were collected and analyzed: (1) the flow rate, and (2) the average speed.

Flow rate analysis

(Figure 6) shows the rate of flow in different CACC penetration levels and different arrival rates.

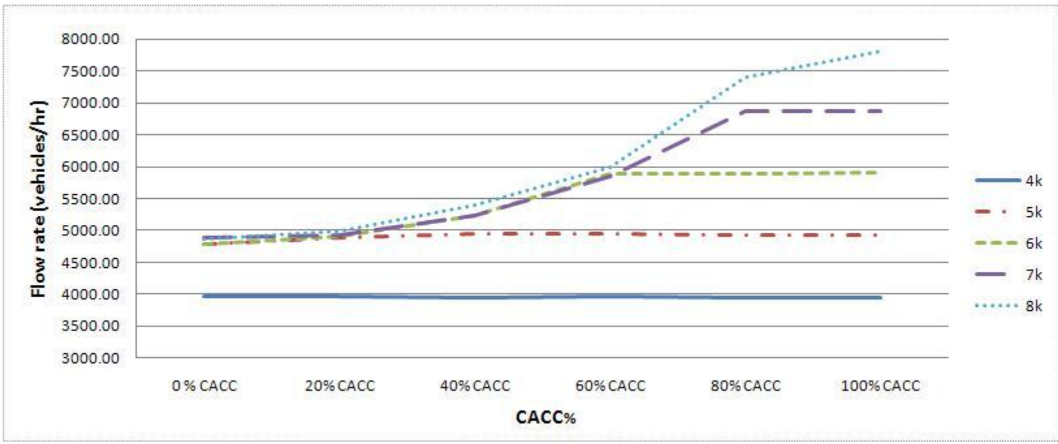

Figure 6. Flow rate analysis (with ramp)

After conducting ANOVA, for the 4000 veh/hr arrival rate scenario (free flow traffic), the flow tends to remain the same unaffected by the different CACC penetration levels. A nearly similar behavior but with a higher flow rate is observed in the 5000 veh/hr arrival rate. The CACC penetration's impact on the traffic flow in low traffic arrival rates is not considerable because the maximum capacity is already reached. In other words, even in lower CACC penetration rates, the maximum capacity of the highway (equivalent to the arrival rate) is reached and the operating CACC vehicles could not increase it because most of the vehicles entering the system are already flowing at free flow speed. The CACC impact is observed in the higher arrival rate scenario of 6000 veh/hr as an exponential increase in the flow rate is observed at a 20% CACC until 60% CACC but the increase was not statistically significant in higher CACC penetration levels. In the 7000 veh/hr arrival rate scenario, a proportional exponential increase of flow relative to the CACC penetration is observed. After a CACC penetration of 80%, no significant increase in the flow rate is observed. In the highest arrival rate scenario (i.e. 8000 veh/hr arrival rate), the flow is proportional to the increase of CACC penetration rate. At 100% CACC and at 8000 veh/hr arrrival rate, the highest flow of 7806.74 veh/hr (per four lanes) or 1951.68 veh/hr/lane is achieved, and is increasing directly proportional to the CACC penetration and arrival rate.

It was concluded from the results of 4000 veh/hr, 5000 veh/hr, and 6000 veh/hr that the effect of CACC on the traffic flow rate in low traffic hours (or low arrival rates) is minimal because the traffic flow is already running in free flow conditions. However, the impact of CACC is maximal in high traffic hours, and especially in high CACC market penetration levels, as shown in cases with CACC penetration rate of 40% or higher (in high arrival rates, significance is observed in CACC penetration as low as 40%).

Average Speed analysis

Likewise, in comparing the average speed between all the scenarios with CACC penetration rate to the reference case without CACC, most of the results showed statistical significance after performing ANOVA. (Figure 7) shows the improvement of the average speed proportional (to some extent) to the CACC penetration rate in most of the cases. In higher CACC penetration rates, the increase in speed was not perfectly linear (observe the drop in speed in 60% CACC under 8000 veh/hr arrival rate for instance). After conducting a Dunnett T3 Post hoc, statistical significance was found in all the cases except the transition between 0% CACC and 20% CACC (at low arrival rates) where the effect of CACC was positive but not significant; and the transition between 60% CACC and 80% CACC (at high arrival rates) where there was a drop in the speed but not statistically significant. As the only drop in speed (that was not proportional to the CACC penetration) was not significant, we concluded that the overall effect of CACC is proportional to the increase in the average speed detected by the speed loop detector.

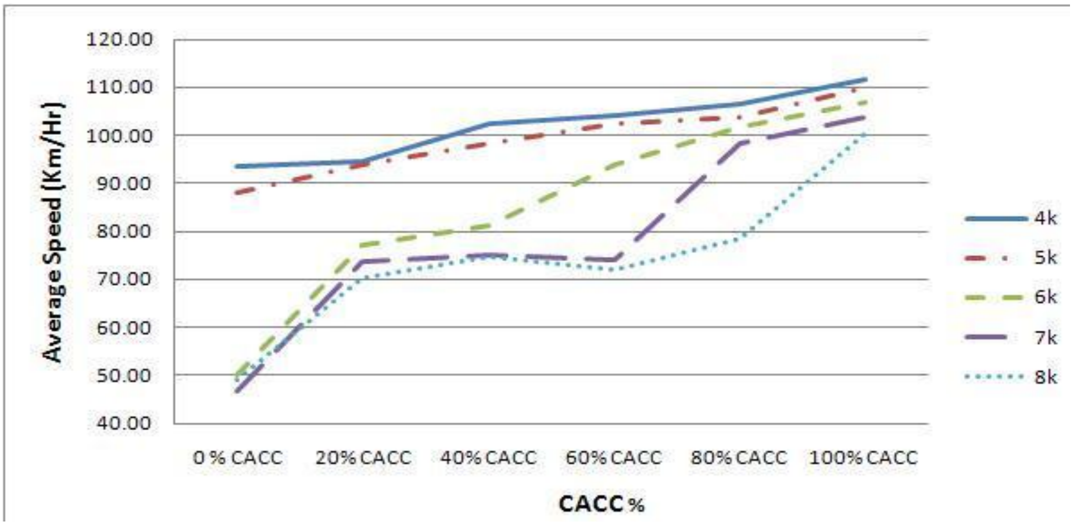

Figure 7. Average speed analysis (with ramp)

This claim was further validated by running a sequential quadratic programming regression analysis using SPSS. The optimal solution was found and the forecasted model equation generated is:

$$Z1 = 147.19 - 15.1\, ar + 0.017\, pr + 0.074\, ar * pr + 0.309\, ar \hat{}2 - 0.001\, pr \hat{}2 \qquad (1)$$

Equation 1. Forecasted model equation generated

Where: *ar*: arrival rate of the vehicles and *pr*: CACC penetration rate

To measure the variability of the flow in the model, the r-squared was calculated. The resulted r-squared, 0.79 is high and indicates a good fit.

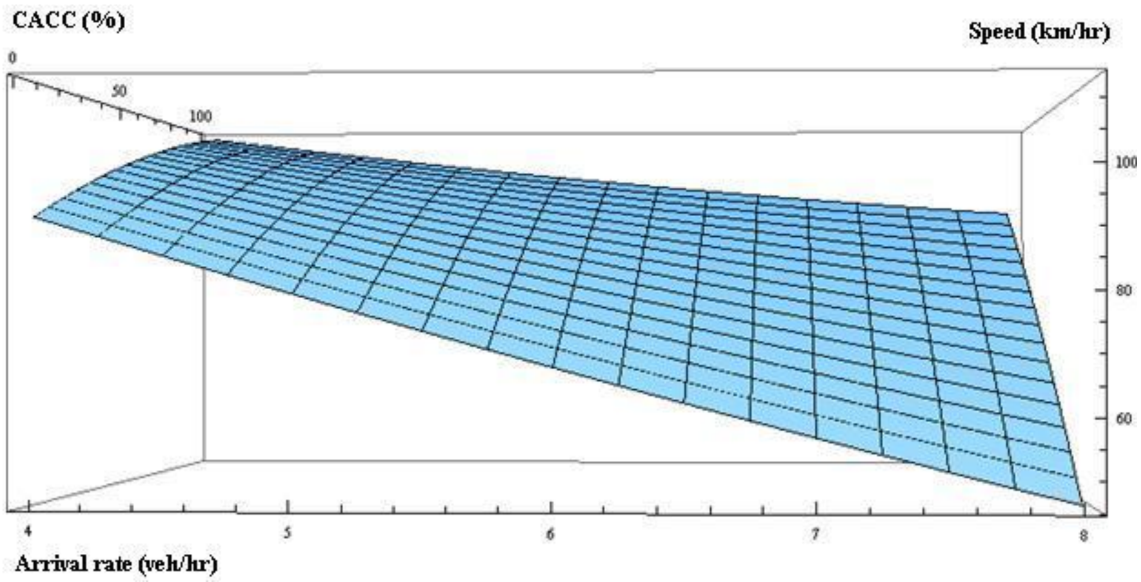

Figure 8a. 3D graph of the average speed of the generated model (with ramp)

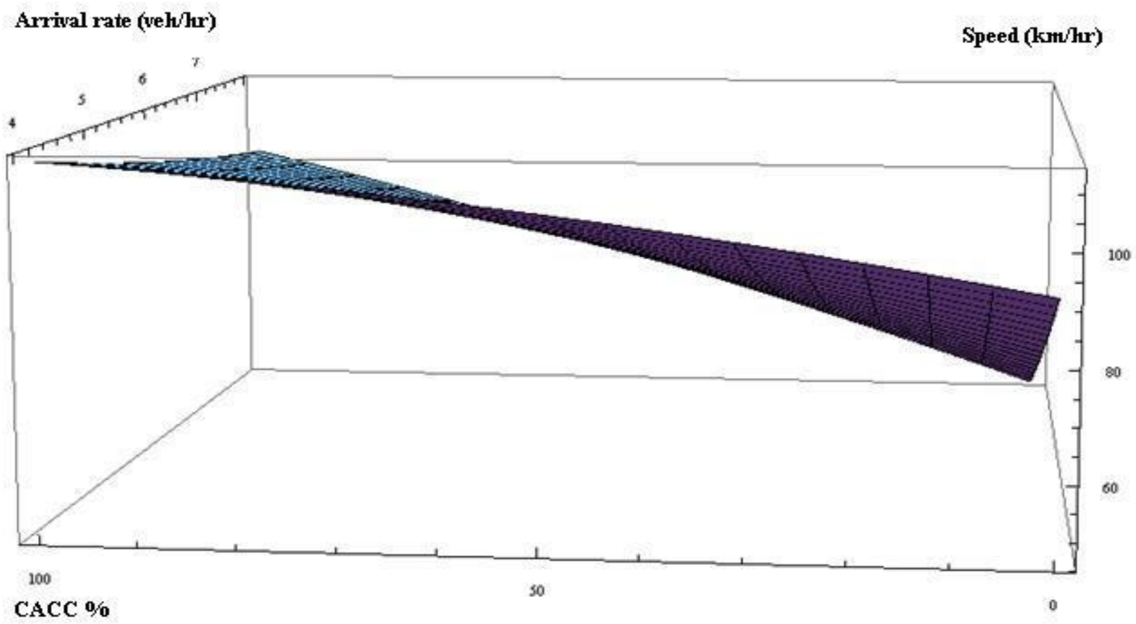

Figure 8b. 3D graph of the average speed of the generated model (with ramp)

(Figure 8a) shows a 3D graph of the average speed of the generated model. The graph shows the direct inverse linear relation between the arrival rate and the average speed that was discussed earlier. In addition, the graph shows that with higher CACC market penetration, the average speed tend to be higher. In (figure

8b), the non linear nature of the decrease in the average speed is observed. In high CACC penetration levels, the decrease in the speed tends to be significantly slower in higher CACC penetration levels. In other words, the average speed at high CACC penetration levels (although decreasing with the increasing arrival rate), is higher than the average speed at lower CACC penetration levels (refer to (figure 8b) to examine the difference).

4.2 Experiments and analysis without a ramp

In addition, experiments were modeled using F.A.S.T. on a 6 km highway without an on-ramp to model the effect of 'natural' shockwaves (shockwaves resulting only from vehicles' decelerations) on traffic performance without the impact of vehicles flowing from an on-ramp creating perturbations in the flow. Three types of experiments were conducted in this phase: (1) the base reference case of 0% CACC, (2) having 20% CACC scattered on all the four available lanes (referred to as 20% CACC Scattered), and (3) 20% CACC restricted on the special HOV lanes with the same HOV rules and conditions applied in section 4.2 (referred to as 20% CACC HOV). Different arrival rates of 7000 veh/hr, 8000 veh/hr, 9000 veh/hr, and 10000 veh/hr were modeled. Higher arrival rates were chosen because of the absence of the on-ramp that plays a major role in creating perturbations that ultimately lead to traffic congestions. The arrival rates of 7000 veh/hr and 8000 veh/hr are cases where no traffic congestions occurred (low traffic hours). The arrival rates of 9000 veh/hr and 10000 veh/hr are cases where traffic congestions were observed (high traffic hours).

Flow rate analysis (without the ramp)

(Figure 9) shows the rate of flow in different CACC penetration levels and different arrival rates. After conducting ANOVA, at the low arrival rates of 7000 veh/hr and 8000 veh/hr (under to moderately saturated traffic), there was no significance in all the CACC penetration levels showing that the CACC impact is minimal because the traffic is already running at free flow the capacity is reached without the CACC penetration. At higher arrival rates, the 9000 veh/hr the CACC cases performed better (higher flow) and showed significance in all the CACC penetration cases except at 20% CACC where no significance was found ($p = 0.797$).

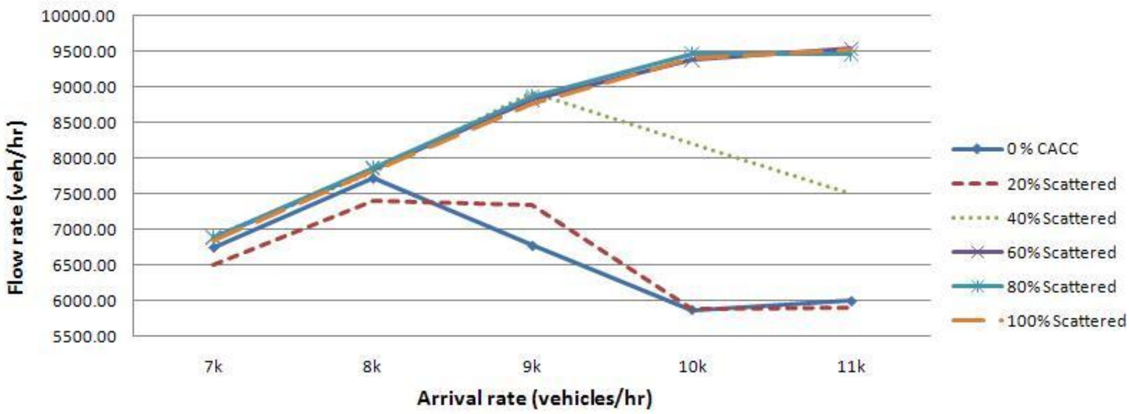

Figure 9. Flow rate analysis (without a ramp)

At 10000 veh/hr, the same behavior was observed where all the CACC penetration levels showed significance except the low CACC penetration of 20% CACC where no statistical significance was found (p= 1.0). After conducting a Dunnett T3 Post hoc analysis, it was concluded that at the high arrival rates of 9000 veh/hr and 10.000 veh/hr, there was no significance in the CACC penetration rates as 60% CACC was a sufficient rate to reach the capacity of the freeway at that arrival rate. Note, that at higher arrival rates of 11000 veh/hr and more, the flow is in fact proportional to the arrival rate and the CACC penetration. Such experiments were not mentioned because the superiority of having CACC embedded on the freeway compared to not having these cars was already proven in terms of traffic flow. Also, the system at 0% CACC could not model accurately the high arrival rates (higher than 10000 veh/hr) as queues will stretch out and reach the entrance of the system not allowing new agents to flow in the system. This shows that at 0% CACC the highest capacity achieved is around 7800 veh/hr or 1950 veh/hr/ln. Conducting experiments with higher arrival rate would not yield accurate results.

As this concludes that the CACC systems have a significant impact on the traffic flow especially at high market penetration, a low penetration of CACC is identified. In order to see a significant CACC impact, the lowest CACC market penetration rate needed is 40% CACC, because at lower levels, no statistical significance was observed.

Average Speed analysis (without the ramp)

(Figure 10) shows the average speed in different CACC penetration levels and different arrival rates. As the speed is decreasing in all the scenarios, a slower and smoother decrease in speed is observed at higher rates of CACC.

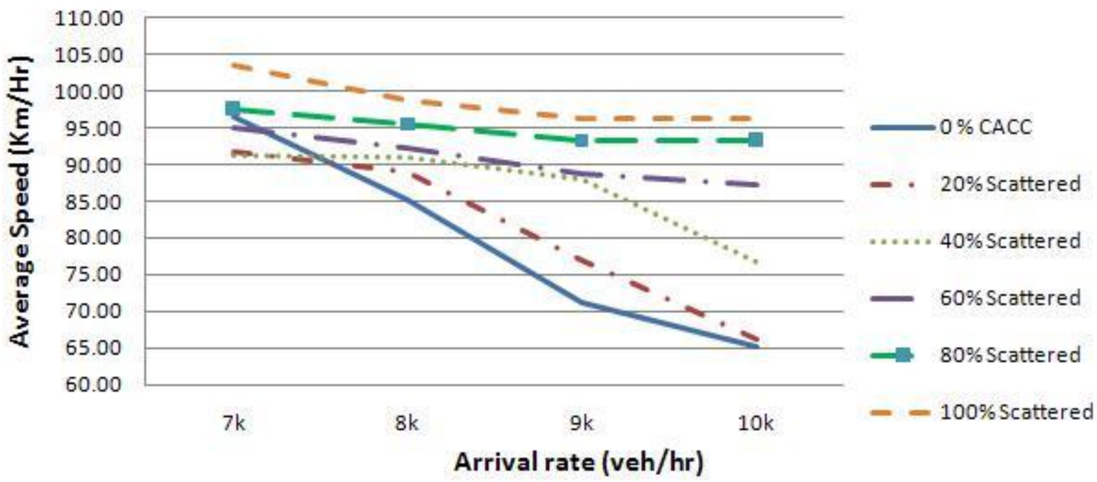

Figure 10. Average speed analysis (without a ramp)

After conducting ANOVA, the 7000 veh/hr arrival rate showed an improvement of the average speed at CACC penetration rates of 40% and more. At higher arrival rates, the impact of CACC was observed at penetrations above 20% CACC. In all these cases, the average speed was proportional to the CACC market penetration rate. Thus, it is concluded in this section that the average speed is highly affected by the CACC system and proportional to the CACC market penetration.

5 Summary and discussion

In this paper, we validated a previously proposed traffic simulation model, F.A.S.T., and analyzed the impact of CACC vehicles on traffic dynamics, the flow rate and the average speed in particular. After conducting two different scenarios, one with an on-ramp and another one without it, the results showed that CACC has a significant positive impact on the flow and average speed. The CACC could highly increase the capacity of the highway by increasing the average speed and the rate of flow. However, this effect is highly proportional on the CACC market penetration and the arrival rate of the vehicles. At a penetration level of 40% CACC or higher, a significant improvement could be observed in the traffic dynamics.

The superiority of the CACC system was demonstrated in this paper. However, several challenges facing the CACC must be taken into consideration. The public acceptability of the CACC close-gap automated driving is a challenging task as mentioned by (Shladover, 2009) in his study. In addition, reaching a 40% CACC market penetration (or higher) is not going to happen in the near future. Therefore, there is a need for a progressive deployment strategy that serves as a transition phase between a low CACC penetration level, where no impact was observed, and a 40% CACC market penetration, where significant impact was observed.

6 Future work

The proposed traffic simulation model F.A.S.T. will be extended to allow accidents to occur making the system more realistic. Other realistic behaviors could be added like emergency vehicles, work zones, weather conditions, etc to be used as other sources of perturbations. Also, as part of the future work, we plan to optimize the performance of the CACC algorithms to cope dynamically with the traffic arrival rates and density. Finally, this study did not deal with platooning and the possible negative impact of platoon splitting (in case a vehicle wanted to split from a platoon). Therefore, we plan to implement effective platooning for best platooning practices, as part of the CACC algorithm in F.A.S.T.

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