2.12 Reducing Traffic Congestions by Introducing CACC-vehicles on a Multi-lane Highway Using Agent-Based Approach

Reducing Traffic Congestions by Introducing CACC-vehicles on a Multi-lane Highway Using Agent-Based Approach

Georges M. Arnaout - Ph.D. Candidate
Old Dominion University
garna001@odu.edu

Shannon R. Bowling - Ph.D.
Old Dominion University
sbowling@odu.edu

Abstract. Traffic congestion is an ongoing problem of great interest to researchers from different areas in academia. With the emerging technology for inter-vehicle communication, vehicles have the ability to exchange information with predecessors by wireless communication. In this paper, we present an agent-based model of traffic congestion and examine the impact of having CACC (Cooperative Adaptive Cruise Control) embedded vehicle(s) on a highway system consisting of 4 traffic lanes without overtaking. In our model, CACC vehicles adapt their acceleration/deceleration according to vehicle-to-vehicle inter-communication. We analyze the average speed of the cars, the shockwaves, and the evolution of traffic congestion throughout the lifecycle of the model. The study identifies how CACC vehicles affect the dynamics of traffic flow on a complex network and reduce the oscillatory behavior (stop and go) resulting from the acceleration/deceleration of the vehicles.
Keywords: *Adaptive Cruise Control, Cooperative Adaptive Cruise Control, agent-based traffic simulation, intelligent vehicles.*

1. INTRODUCTION

Traffic congestion has been a growing problem and a burden to the American economy and society for many decades, with no short term solutions being established to combat it. Everyone is affected by traffic congestions on a daily basis, especially in large and populated cities such as Los Angeles, Austin, and Washington DC. The negative effects are numerous including most importantly: productivity losses, increased accidents, higher carbon emissions, more fossil fuels consumption, and many more.

The government has been trying to cope with the increasing demand (i.e. the increasing number of vehicles) by building more roads and highways, which is a strategy that on one hand, generates tremendous expenses to the economy, and on the other hand, and more importantly, is no longer feasible as most of the major traffic cities have already reached the maximum capacity for roads and highways.

With the continuing progress of artificial intelligence and wireless technology, and particularly vehicle-to-vehicle inter-communication, long-term solutions for the traffic congestion problem are starting to appear. After the advent of telematics technology in transportation and traffic, the expectations of this technology are high not only because it increases the driver's safety and comfort, but because the efficient use of this technology has the potential of improving the traffic flow and reducing traffic congestions on freeways [1], if widely adopted. Amid the continuing success of the ACC (Adaptive Cruise Control) technology introduced to the car market in the nineties, the attention has shifted to a more efficient and promising but more complicated technology – the CACC (Cooperative Adaptive Cruise Control).

As the research in this area is still lacking, the purpose of this study is to contribute a working agent-based model of a 4-lanes highway system having CACC embedded vehicle(s) without overtaking (i.e. vehicles do not perform lane changes). Different scenarios will be conducted to examine how CACC vehicles influence the dynamics of traffic flow on a complex network. Conclusions will be made based on the model's results.

2. LITERATURE REVIEW

It has been shown over the years that computer simulation models can help the practicing transportation engineers to better understand the highway systems, allowing them to analyze

everyday traffic management needs by looking at congestion problems and understanding their cause. Traffic simulation allows transportation engineers to examine behaviors that are not apparent through visual observation. Three types of simulations have been found in the literature pertaining to traffic simulation: (1) Microscopic – model focuses on individual vehicle progress and movements; (2) Macroscopic – model focuses on the overall traffic flow such as the mean speed, variance, flow rate, density, etc ; and (3) Mesoscopic – model focuses on individual vehicles at the aggregate level by speed density relationship and queuing theory approaches [2]. According to the literature [3] and [4] , ACC could have both, a positive as well as a negative effect on the traffic flow. [5] examine how a low penetration level of ACC does not have any effect on traffic flow, regardless of the time-gap set.. With a relatively high penetration of ACC (between 20% and 60%) in the market, and even under the most advantageous conditions, an ideal ACC system can only have a small impact on highway capacity [6]. ACC vehicles are currently developed by the car industry and their penetration is relatively low. With an average time gap of 1.4 seconds between ACC and other vehicles, the highway capacity can be increased by at most 7% [6]. Additionally, the same study has shown that with a penetration of ACC above 60%, the effect of ACC can be negative and can lead to a modest loss of highway capacity.

Unlike ACC, the literature pertaining to CACC is limited. Several studies examined CACC designs and architectures but most of the studies did not explore the traffic flow effects of CACC in terms of throughput, capacity, and congestion reduction. One of the very few studies that targeted this area of research was [6], where it identified that CACC vehicles enable closer vehicle following (time gap as low as 0.5 seconds) 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 was 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. CACC allows vehicles to communicate together and share important traffic information by transmitting information about incidents, speeds, positions, destinations, congestions from preceding vehicles, and emergencies [6]. Cooperative Following (CF) uses automated longitudinal control combined with inter-vehicle wireless communication allowing equipped vehicles to anticipate sudden and severe braking [7]. CF reduces shockwaves and smoothens the traffic flow and also improves the traffic safety.

The following two conclusions can be drawn from the literature review:
1-   As the high rate of ACC market penetration could affect the traffic flow negatively, the research must focus more on the CACC rather than the ACC technology.
2-   Extensive research is needed to study the effect of CACC on the freeway traffic flow in terms of throughput, congestion reduction, and capacity.

3. PROBLEM STATEMENT

With the occurring traffic congestions, there is a need to better manage the use of existing infrastructure in order to make the highway system more efficient and sustainable for the twenty-first century. The approach of our study is to better manage the existing capacity rather than looking into different ways of how to increase it. From the literature and our extensive observation of traffic congestions, one of the main causes of traffic on freeways is the continuing shockwaves, resulting from sudden vehicles braking, which create oscillations resulting in small traffic jams. With a limited highway capacity compared to the number of vehicles in operation, the small traffic jams ultimately become bottlenecks resulting in bumper-to-bumper traffic.

In this paper, we present an agent-based model of traffic congestion and examine the impact of having multiple CACC embedded vehicle(s) on a highway system consisting of 4 traffic lanes without overtaking. In a previous study [8], we worked on a model with a single lane and a single CACC car examining its impact on the traffic flow. This study is a continuation of the latter study. We examine the impact of having multiple CACC cars on 4 separate lanes with different traffic patterns (between cars, trucks, and CACC vehicles). In our agent-based model,

CACC vehicles adapt their acceleration/deceleration according to vehicle-to-vehicle inter-communication. We analyze the average speed of the cars, the shockwaves, the evolution of traffic congestion, and other parameters throughout the lifecycle of the model. Failures in the operation of the sensors and communication equipment were not taken into consideration.

4. SIMULATION MODEL

The object-oriented model is developed using Java® general-purpose language. The microscopic traffic simulation model built is an expansion of an open-source model originally developed by [9]. Some of the most important additions to the original model are: adding two additional lanes, increasing the freeway distance from 2.5 Km to 10 Km, collecting macroscopic properties from the model as well as microscopic properties, and most importantly adding CACC vehicles.
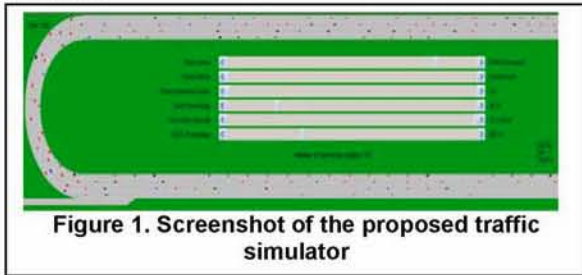

Figure 1. Screenshot of the proposed traffic simulator

As shown in fig. 1, our model consists of a U-shaped 4-laned freeway where ongoing traffic flows anticlockwise where vehicles enter and exit the system after traveling a distance of 10 km. Lane change, overtaking, and weaving are not allowed among vehicles, at this stage of our study. Cars (whether CACC or not) are 4 x 2 meters and trucks are 6 x 2 meters. The range of longitudinal detection of CACC sensors is 30 meters taken from [10]. At this stage, the model proposed does not attempt to find the optimal configuration (or calibration) of the CACC parameters. The proposed model uses the following CACC algorithm:

Phase 1 pseudo code

```
If [speed] of precedent_vehicle < [speed] of
CACC_car AND separating_distance <= 14
meters AND [lane] of precedent_vehicle == [lane]
of CACC_car
{
   Reduce [speed] of CACC_car by x%
}
Else
{
   Increase [speed] of CACC_car by x%
}
```

Phase 2 pseudo code

```
If [type] of precedent_vehicle == "CACC" AND
[lane] of precedent_vehicle == [lane] of
CACC_car
{
   Perform close following // meaning join platoon
with a time gap of 0.5 s
}
```

The algorithm is divided into two phases. The first phase, which is the ACC part of the CACC system, is strictly related to the vehicle directly in front of the CACC vehicle. In this phase, the intelligent car communicates with the car in front of it and adapts its speed according to (a) the separating distance, (b) the lane used, and (c) the speed of the precedent vehicle. If the precedent vehicle was also CACC, close following (i.e. time gap of 0.5 s) can be achieved. Thus a platoon is formed in phase 2. If the precedent vehicle was non-intelligent, the CACC vehicle acts like ACC and maintains a safety distance time gap of 1.4 s using the algorithm stated in phase 1.

In our proposed model, the following parameters were used:

• Speed – speed of the operating vehicles ranging from 0 km/hr (complete stop) to 30.6 ms/frame equivalent to 130km/hr (maximum possible speed for cars) and 26 ms/frame equivalent to 110 km/hr (maximum possible speed for trucks).
• Acceleration – the acceleration of the operating vehicles ranging from 0 to 1 ms/frame.

• Deceleration – the deceleration of the operating vehicles ranging from 0 to -1 ms/frame.
• CACC Percentage – the percentage of CACC vehicles operating on the freeway.
• Time gap – the clearing safety distance between vehicles in time distance
• Truck Percentage – the percentage of trucks operating on the freeway.
• Main Inflow – the arrival rate of vehicles flowing into the freeway.
• Simulation time – each time tick in the model represents one minute.

The basic configuration used in this paper is a four-lane highway with the following parameters:

- The low arrival rate is set to 2000 vehicles/hour
- The high arrival rate is set to 6500 vehicles/hour
- The truck percentage is set to 10% capable of reaching 100%
- The CACC vehicles percentage is set to 0% capable of reaching 100%
- The simulation speed is set to 6.9 times (normal speed). It can be reduced or increased by the modeler.

5. MODEL ASSUMPTIONS AND LIMITATIONS

In this section, we present the model assumptions and limitations:

- Failures in the operation of the sensing and communication equipment of CACC are not considered.
- Only CACC cars are considered. All trucks operating are considered non-intelligent.
- Collisions, work zones, and weather conditions, although they highly affect the traffic flow, are not implemented.
- The CACC system is automatically turned off when a lane change is occurring or when there are no vehicles within the sensor's range of detection. The system is turned back on under normal conditions.
- The model proposed, at this stage, does not attempt to find the optimal configuration of the acceleration and deceleration parameters of the intelligent vehicles.
- The proposed model does not allow overtaking at this point. The current model is still a work in progress.

6. EXPERIMENTS AND RESULTS

We conducted two scenarios in this study. The first one consists of a low arrival rate of 2000 vehicles/hour, and the second consists of a high arrival rate of 6500 vehicles/hour. In each scenario, we introduced different levels of CACC penetration levels (i.e. 0%, 20%, 60%, 80%, and 100%). The cars enter the system with an initial speed set to the maximum – 130 km/hr and the trucks enter with their maximum speed of 110 km/hr. As the vehicles travel anticlockwise and exit the system, we collect statistics and analyze quantitatively the performance of the traffic flow. The results are shown in table 1 and 2. The following statistics are collected: (1) Mean speed, (2) flow of traffic, (3) standard deviation of speed, (4) density, and (5) average time spent in the system by vehicles. The same distance of 10 km is used in all the scenarios. All the simulations were ran 5 times for 30 minutes each. We chose a small number of replications because the results of the simulations were analogous.

Table 1. Scenario 1 results

2000 v/hr Arrival Rate	Mean Speed (km/hr)	Flow (v/hr)	Travel Time (min)	Density (v/km)	Std Dev
0% CACC	120.40	1630.00	5.79	20.08	1.90
20% CACC	119.92	1611.33	5.83	20.12	1.87
60% CACC	120.48	1595.33	5.79	20.11	2.05
80% CACC	120.80	1314.67	5.77	19.86	2.19
100% CACC	121.74	1570.67	5.70	19.81	2.17

Table 2. Scenario 2 results

6500 v/hr Arrival Rate	Mean Speed (km/hr)	Flow (v/hr)	Travel Time (min)	Density (v/km)	Std Dev
0% CACC	85.51	1329.33	7.09	74.70	7.95
20% CACC	84.69	1292.67	7.03	73.47	8.09
60% CACC	98.44	3828.67	6.60	75.01	5.17
80% CACC	106.49	4430.00	6.38	72.98	3.10
100% CACC	107.53	4745.33	6.31	72.31	3.78

In the low arrival rate scenario, the impact of CACC is minimal and leading to a modest loss of highway capacity and performance. Such negative results are not taken critically into account because of the minimal effect of CACC, and because of the fact that at a low arrival rate, the traffic performance is well in all cases.

Most of the study focuses on the high arrival rate scenario because this is the nature of the problem we're dealing with. As CACC vehicles enable closer vehicle following reaching a time gap of 0.5 seconds, significant highway capacity increases have been observed. Figure 2 shows the comparison of different CACC highway penetration in the case of traffic flow performance metric. Figure 3 and fig. 4, show the density and average speed at different CACC penetration levels. We can easily observe how the impact is directly related to the highway penetration. For instance, at 0% CACC penetration, the flow of traffic was slightly better than the case with 20% CACC penetration. With 60% CACC penetration, the average flow achieved a major progress reaching 3828.67 vehicles/hour. Evidently, the impact of CACC vehicles at higher penetration rate is positive. An improvement in all the performance measures collected was observed. At a rate of 0% CACC the flow averaged at 1329.33 vehicles/hour while it averaged at 4745.33 in 100% CACC penetration (almost 3.5 times more). Note here that by 100% CACC penetration, we mean 100% penetration as far as cars. The percentage of trucks (10%) did not change in all the scenarios. With a 100% CACC penetration including trucks the CACC impact can be even better reaching an average flow of 4860 vehicles/hour.
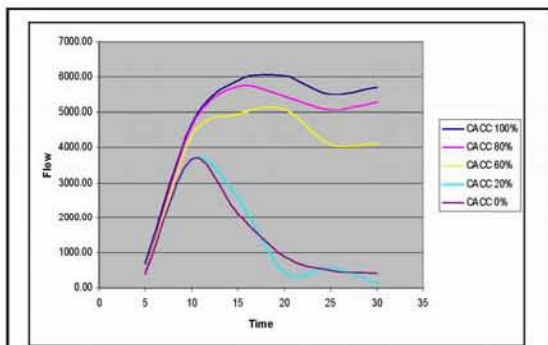

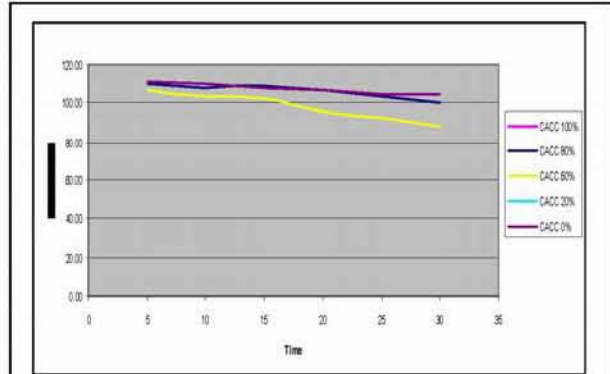**Figure 3. Density at different CACC penetration levels**

Figure 4. Average speed at different CACC penetration levels

7. CONCLUSION

In this paper, we identified the benefits of CACC and its impact on the traffic flow, especially in traffic congestions. We contributed a working prototype of a microscopic traffic simulator that uses macroscopic and microscopic traffic properties to describe the traffic performance. Four main conclusions were drawn from this study:

- At low traffic arrival rates, the impact of CACC is not significant. In some cases, the CACC impact resulted in a modest decrease in traffic performance. Therefore, it is suggested to turn off the CACC system at low traffic arrival rate situations, and activate the ACC system, to provide the driver with comfort and safety without affecting the traffic flow.

- At high traffic arrival rates, the impact of CACC is significantly positive in the cases of a highway penetration higher than 60%. An improvement in all the performance measures collected was observed.

-The CACC impact on traffic flow is directly related to the market penetration. A higher rate of penetration have a significant potential of increasing the highway capacity, while a low rate penetration could have no significant impact or even result in a modest loss of highway capacity.

-Since the CACC high penetration is not occurring in the near future, there is a need for a

progressive deployment strategy, in order to increase the benefit of CACC. One approach, previously suggested by [6], suggests placing CACC vehicles in the same lane by giving them priority access to special lanes (such as HOV lanes). However, this approach has not been validated by any simulation studies.

- This study validated conclusions from two previous studies [1] and [6], that concluded that the impact of CACC at a high market penetration is significantly positive.

8. FUTURE WORK

Simulating traffic flow without overtaking is not realistic, since lane changes have a major impact on the traffic performance. Therefore, in our planned further work, overtaking will be implemented (i.e. cars will perform lane changing and weaving). In addition, the model parameters will be calibrated according to real life empirical freeway data. The CACC acceleration/deceleration parameter (i.e. the x% found in the pseudo code) will be optimized. Finally, as the CACC agents perform platoons, the platoons must be controlled for merging safety. Therefore, we will perform "controlled platooning" meaning that the number of platooning will be limited for more safety in merges (refer to [1])

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