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Exploring the Effects of Cooperative Adaptive Cruise Control in Mitigating Traffic Congestion

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EXPLORING THE EFFECTS OF COOPERATIVE ADAPTIVE CRUISE CONTROL IN MITIGATING TRAFFIC CONGESTION

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ABSTRACT

EXPLORING THE EFFECTS OF COOPERATIVE ADAPTIVE CRUISE CONTROL IN MITIGATING TRAFFIC CONGESTION

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The aim of this research is to examine the impact of CACC (Cooperative Adaptive Cruise Control) equipped vehicles on traffic-flow characteristics of a multilane highway system. The research identifies how CACC vehicles affect the dynamics of traffic flow on a road network and demonstrates the potential benefits of reducing traffic congestion due to stop-and-go traffic conditions. An agent-based traffic simulation model is developed specifically to examine the effect of these intelligent vehicles on the traffic flow dynamics. Traffic performance metrics characterizing the evolution of traffic congestion throughout the road network, are analyzed. Different CACC penetration levels are studied.

The positive impact of the CACC technology is demonstrated and shown that it has an impact of increasing the highway capacity and mitigating traffic congestions. This effect is sensitive to the market penetration and the traffic arrival rate. In addition, a progressive deployment strategy for CACC is proposed and validated.

*This dissertation is dedicated to my Father, **Michael Arnaout** – my personal idol, and the one who gave me every opportunity to realize my dreams.*

PS: I guess those high school private lessons eventually did pay off…

ACKNOWLEDGMENTS

One day, about three years ago, I set out on a jog, iPod loud, playing an album for Muse, while running in the streets of Norfolk, Virginia, trying to organize my thoughts and finally make up my mind. As I was always used to take my brother's advice in most of the important decisions in my life, his advice a few days ago was "Go for it". Deciding to take his advice, I set out to prepare myself for a journey called Ph.D., that at the beginning I wasn't too sure about.

Thus, the first person I would like to acknowledge, for both personal and professional reasons, is the person responsible for me being here and choosing this path, my older brother JP who was always there for me. I can never thank you enough for this. Cliché as it is, there are seriously no words to express my gratitude.

The completion of this dissertation would not be possible without the support of many people. I would like to express my deep gratitude to my advisor, Dr. Shannon Bowling. For more than three years, he kept providing encouragement, outstanding teaching, and lots of great ideas. He is not only an advisor who advises me, but also a friend who kept working with me side by side on those long days in Kaufman Hall. His enthusiasm and outside-the-box thinking helped me to become a successful researcher. Dr. Bowling is brilliant, absolutely brilliant. So, Dr. Bowling, thank you for sharing your brilliance with me.

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Since music has always played a major part in my life (and this dissertation), I feel compelled to mention the music that I listened to while running those long lab experiments (around 2000 of them) and writing this dissertation. I listened to: Muse, Jack Johnson, Tiesto, Armin Van Burren, Coldplay, Dream Theater, Ziad Rahbani's oriental jazz, Red Hot Chili Peppers, Rammstein (as extreme as that might sound), Dave Matthews Band, Chemical Romance, Cake, and Thievery Corporation.

I would like to thank those individuals and groups who have provided diversions from this project that have given me the occasional rest and relaxation that I needed. These include the members (including the non official "bartenders" Joey and Salim) of the F.O.R.E.I.G.N.E.R.S. (for better or worse), my very close friend Youssef Taghlabi who gave me the best advices in my life, and Hadi Arbabi (or soon to be Dr. Arbabi) for his valuable advices. He is an expert in Intelligent Transportation Systems and his ideas and knowledge brought great value to my research from a different point of view. Special thanks belong to Ihar Bahdanau and my lovely Dr. Evelyne Khoriaty, who had to deal with my mood swings and constant nagging in the last months.

This dissertation was not an easy task for me. At several occasions, I felt frustrated but I never stopped. And for that, I am forever grateful to my parents and for the way they have raised me that one must certainly work hard and play hard to live happily. I will always be grateful for having the two greatest parents anyone could ask for, my father Michael and my mother Mayda. I would not be where I am today—and in the future—without their love, support, and constant sense of joy in seeing their children happy in life. I am proud of the person I have become, but I am even more proud of the person I will become.

PS: Michael, I know you've always wanted a Doctor in the house, I might not be that kind of Doctor, but if this will make you feel any better, call me "Doctor Arnaout!"

NOMENCLATURE

V_a ACC equipped vehicle

V_c CACC equipped vehicle

V_f Discovered front vehicle

$d(x,y)$ Distance from x to y

O_f Front object ahead of a vehicle

D_r Range of radar detection of a radar equipped vehicle

D_n Range of DSRC (Dedicated Short Range Communication) detection

T_c The time between the rear end of the lead vehicle and the front end of the following CACC vehicle pass the same location along the roadway (in seconds)

T_m The time between the rear end of the lead vehicle and the front end of the following manual vehicle pass the same location along the roadway (in seconds)

g_s Safety gap to avoid collision between vehicles. It is the distance corresponding to the time gap T

d_v Speed differential – increase/decrease in the speed of the vehicle

e Acceptable error in position

q average flow rate of the traffic

k average density of the traffic

v average speed of the traffic

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CHAPTER 1

INTRODUCTION

As a large and growing burden on the American economy and society, traffic congestion occurs for a variety of reasons, and more than one mechanism is needed to solve this ongoing problem. An economist, Anthony Downs, argues in his book (Downs 2004) that it is impossible to fully solve the problem of traffic congestion. Because of the rush hour, traffic congestion is inevitable. By having a standard work day, the demand for automobile travel is simply larger than the supply of roads. As a result, at peak hours, traffic jams are unavoidable.

One of the main causes of traffic congestion is the increase in traffic demand. By having more demand than supply, any minor perturbation in the traffic could lead ultimately to a traffic jam. Another major cause is the stop-and-go effect, also known as the shockwave effect, resulting from small fluctuations in speeds (in saturated traffic conditions) when drivers accelerate and/or decelerate wanting to keep an appropriate driving distance (or headway space) between other drivers. Once the traffic density reaches a critical state, the cumulative effect of the speed fluctuation propagates back over the drivers like a shockwave and ultimately leads to a standstill traffic jam. Other causes for stop-and-go traffic are ramps, work zones, accidents, emergency vehicles, or severe weather conditions.

The consequences of traffic congestion are numerous. Motorists and passengers waste valuable time getting stuck in traffic queues. Such delays may result in late arrivals for employment, education, and product delivery. This non-productivity results in a reduction in regional economic health. This also adds additional expenses on the businesses by delaying shipments of goods, therefore reducing the nation's productivity. Increased vehicles' idling results in wasted fuel and more gas emissions from increased carbon dioxide emissions, which has a horrifying negative effect on the environment. Increased idling in traffic accompanied by excessive braking also has an impact on the wear and tear of the vehicles. As the motorists battle on the highways to reach their destinations on time, this increases stress, road rage, and most importantly the risks of accidents, therefore reducing the traffic safety and the health of the motorists. According to Automobile Association of America (AAA), the number of traffic fatalities in 2009 was almost 34,000, and car accidents cost more than $164 billion a year (Clifford 2008). An indirect consequence of traffic congestion often ignored by society is the spillover effect. As motorists attempt to escape the congested roads and take alternative routes, a concept known as "Rat-Running", the side streets or short-cuts taken affect the real estate prices of the visited neighborhood negatively. The United States saw large increases in both motorization and urbanization starting in the 1920s that led to migration of the population from the sparsely populated rural areas and the densely packed urban areas into suburbs (Henderson 2003).

Government authorities have been trying to solve the classic demand and supply traffic congestion problem for decades either by increasing the capacity (increasing supply) - building additional roads, or by reducing the number of operating vehicles (reducing demand) – investing more in public transportation. It is an ongoing debate which approach is more successful for combating traffic. The approach of this study lies in the middle.

As building more roads and highways is often not feasible, due to the great expense and because most of the major traffic cities have already reached the maximum capacity for roads and highways, and with the continuing progress of artificial intelligence and wireless technology, the emphasis has turned to telematics technology integrated with Advanced Driver Assistance Systems (ADAS). ADAS technology is proven to contribute to the solution of the problem faced, in the long term. ADAS are systems that assist the driver in the driving process, aiming to provide more safety and comfort for the driver. 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. 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 red vehicle or the preceding vehicle in this case) has the ability of detecting the speed and distance of the preceding vehicle or any other obstacle ahead. Thus, if the preceding vehicle decelerates, the braking system of the ACC vehicle is signaled to decelerate. If the preceding vehicle accelerates again, the engine is signaled to accelerate, limited by the initial cruise control speed set initially by the driver. Other than providing comfort and safety to the drivers, another advantage of the ACC system is that it helps drivers anticipate the braking of the preceding vehicles, and therefore brake more smoothly reducing the shockwave effect. ACC equipped vehicles still have a low penetration in the car market. The entry-level high-end luxury models that have optional adaptive cruise control include the Audi A4, BMW 328i, Ford Taurus, Lexus IS250 and Infiniti G37. ACC is expected to become widely available in the car market as the cost of the technology drops and the ACC system becomes more standardized.

Another technology that is starting to appear amid the continuing progress of vehicle-to-vehicle communication is the Cooperative Adaptive Cruise Control (CACC). CACC is a technology that is more efficient than ACC but more complicated. CACC is a more advanced technology providing the CACC equipped vehicle with more accurate information about the preceding vehicle through fast and real-time vehicle-to-vehicle information sharing among CACC equipped vehicles, as shown in figure 2. The impact of CACC on the traffic flow and safety is still uncertain due to the lack of research in this area. Since the CACC concept is relatively new, CACC equipped vehicles have yet to appear in the car market.

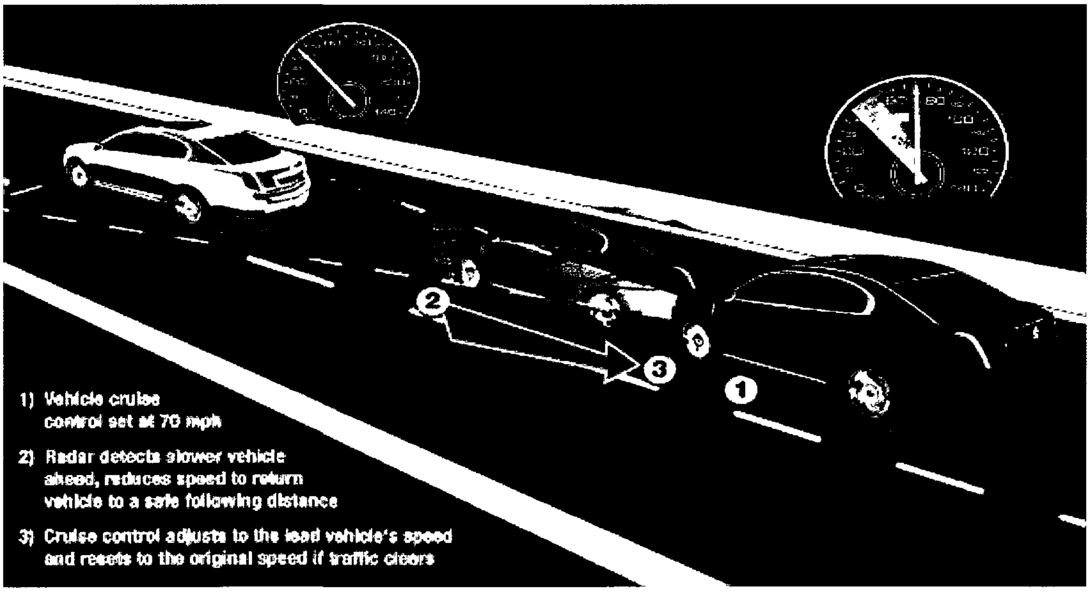


Figure 1. Adaptive Cruise Control system (figure taken from (Motion-Trends 2010))

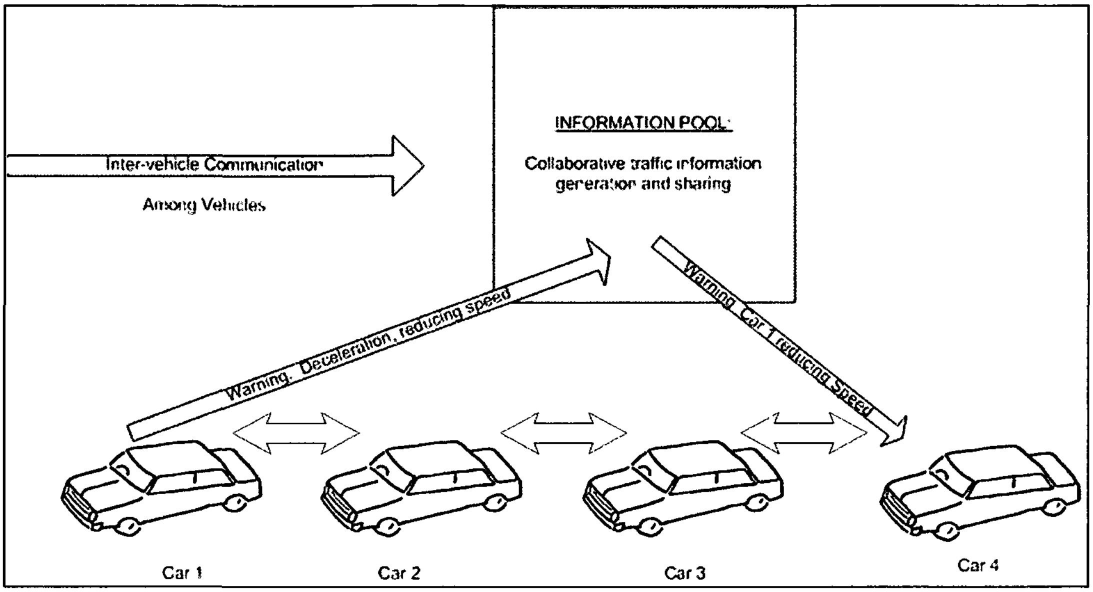


Figure 2. Sharing traffic information among CACC vehicles

1.1 Area of the research

Motivated by the recent developments of vehicle-to-vehicle communication via Vehicular Ad-hoc Networks (VANETs), and the potential of vehicles sharing traffic information to tackle traffic congestion and impact the traffic dynamics positively, this research was oriented towards intelligent transportation systems and particularly focused on Cooperative Adaptive Cruise Control systems, and their effect on traffic dynamics. The latter's growing popularity is still premature due to the lack of literature pertaining to this topic. 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.

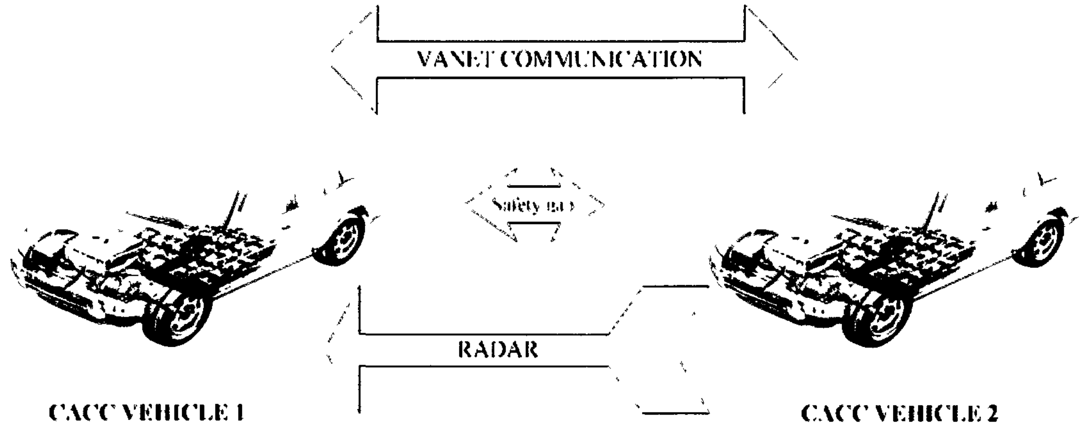


Figure 3. Vehicle-to-Vehicle communication through VANETs and Radar

CACC equipped vehicles have the advantage of using radar technology (or other technologies like Lidar) as well as wireless inter-vehicle communication via VANETs to gain superior ability of predicting the state of traffic and make appropriate speed modifications to avoid a traffic jam (see figure 3). By being able to share real time traffic information with other vehicles, CACC equipped vehicles have a potential of increasing the traffic string stability and reducing oscillations that result in stop-and-go, by smoothing the driver's reaction to the acceleration and deceleration of other motorists.

1.2 Background and Scope of Research

The interest in Intelligent Transportation Systems (ITS) is continuing to grow as many researchers consider ITS applications as possible solutions for the traffic congestion problem. By combining information technology and communications, ITS systems have a potential of greatly affecting the driver's experience as far as (1) safety, (2) comfort, and (3) traffic jam avoidance. Recently, the United States has been very involved in ITS projects. ITS systems vary in their functionalities and their relative technologies applied.

From car navigation, advanced traffic signal control, automatic car-plate recognition systems, to roadways surveillance and mass evacuation of people in case of threats or natural disaster, ITS has become a legitimate field of study.

To familiarize the committee with the scope of the proposed research, a basic chart of the research problem has been created, shown in figure 4. ADAS is a technology intended strictly for the driver's safety and comfort. From reinforced car structures to driver drowsiness detection, ADAS systems have a major impact on reducing the number of accident-related deaths in the United States. In fact, the number of deaths relative to the total U.S. population has declined 35.5 percent between 1979 and 2005 (Intermap-Technologies 2009).

Combining ADAS technology with ITS, opens a new frontier for transportation research. A visionary ITS project that is recently gaining more popularity is driverless cars. Driverless cars are vehicles equipped with an autopilot system, having fully automated driving capabilities (Benenson, Petti et al. 2008). The latest projects involving driverless cars include the DARPA Grand Challenge and Google Driverless car. However, the trend in ITS studies has been to move the research efforts from the more futuristic projects to the more short-term projects. By adding ITS vehicle-to-vehicle communication to existing ADAS systems, the research focuses on smart cars, and more particularly on IntelliDrive and CACC systems.

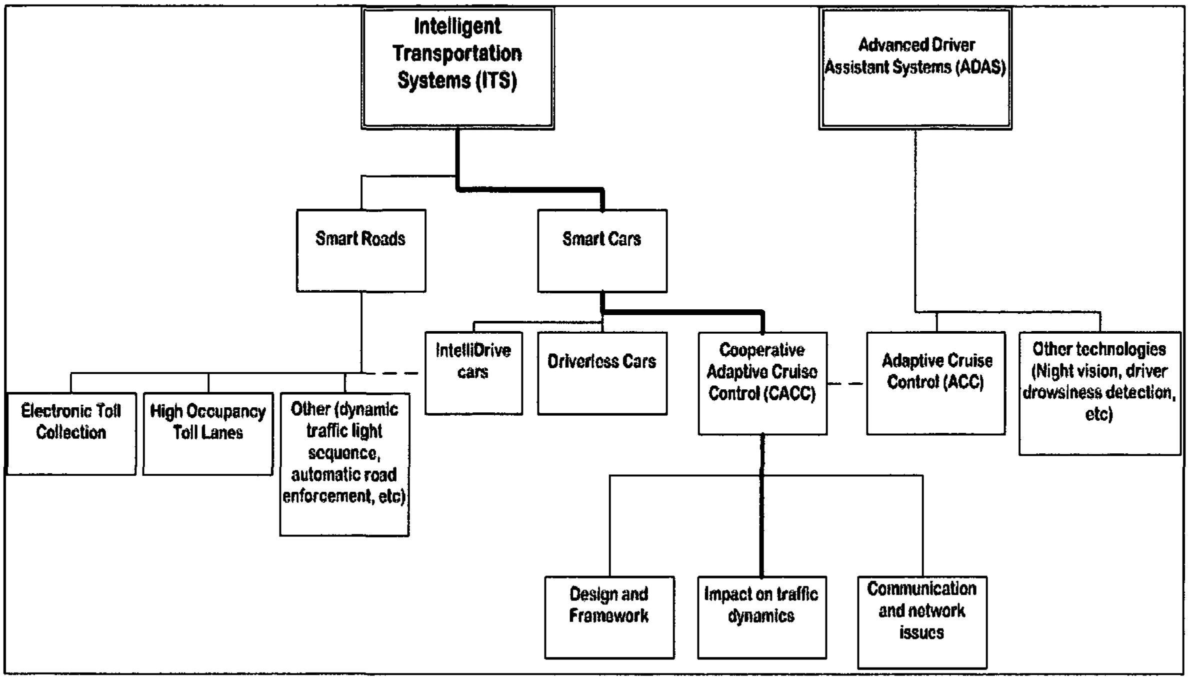


Figure 4. Scope of the research problem (follow the bold line)

The US Department of Transportation (DOT) has launched the IntelliDrive initiative (USDOT 2010) aiming to reduce the number of traffic accidents in the US. IntelliDrive applications are expected to provide connectivity (1) among vehicles, (2) between vehicles and the infrastructure, and (3) among vehicles, infrastructure, and wireless devices. As the implementation of IntelliDrive on US highways is still many years away from implementation, the proposed research looks into a combination of the existing ADAS technology, ACC, and ITS, resulting in smart ACC systems or CACC. Although CACC vehicles have yet to appear in the market, several projects have already implemented prototype vehicles carrying this technology, like (Shladover 2009). The main advantage of CACC vehicles over IntelliDrive vehicles is that they don't require communication with Transportation System Operators (TSO) nor with the infrastructure through Road Side Units (RSU), making their implementation a faster process.

1.2.1 Impact of CACC on highways

In this area of research, the focus is on the CACC effect on the traffic characteristics of highways. It is not possible to estimate the effect of CACC systems from field tests because the technology does not exist in the car markets. Some projects created prototypes of CACC equipped vehicles, but their number is extremely small to predict the overall impact of CACC systems on the traffic dynamics. Thus, in this area of research, simulation is used to model the traffic and implement CACC equipped vehicles on the highways, then analyze their impact on the traffic flow and dynamics.

1.2.2 Vehicle-to-Vehicle Communication

Vehicle-to-vehicle communication uses Dedicated Short Range Communications (DSRC) based on wireless Local Area Network (WLAN) technology (Cheng, Henty et al. 2007). Roadside units (RSUs) could be used to transmit traffic data between vehicles on the highways, assuring a steady communication among the vehicles. The traffic data exchange takes place automatically via VANETs without any intervention needed from the driver's part. This area of research focuses on the networking part of CACC and the performance and quality of the real-time traffic data exchange among the participating vehicles.

1.2.3 CACC Design and Framework

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 and frameworks, aiming to standardize and optimize the use of the technology.

This dissertation is concerned with the first sub-area, by studying the impact of CACC systems on the traffic dynamics. Using simulation, the study will analyze the impact of having CACC equipped vehicles embedded on freeways, in different penetration rates. In addition, a CACC algorithm will be proposed for collaborative driving among equipped vehicles.

1.3 Purpose of the Research

The purpose of this study, then, is to gain insight on how CACC systems could affect the traffic dynamics and to what level. Specifically, the study will focus on two primary objectives:

1- To validate results from previous studies pertaining to the impact of CACC systems on traffic dynamics.

2- To determine a progressive deployment strategy that serves as a transition phase between a low CACC penetration level and a fully CACC-equipped highway.

In addition, because very little is known about the effect of CACC systems on the traffic dynamics, a third objective will be to contribute the following:

3- To examine various methods and approaches in studying Cooperative Adaptive Cruise Control systems. In other words, provide a traffic simulation model in which existing and/or other CACC algorithms may be tested. The contributed open-source microscopic agent-based model is expected to be more flexible than other developed microscopic traffic models available in the literature.

4- Present an Efficient CACC (ECACC) algorithm for semi-autonomous CACC systems based on the use of agent technology and information sharing. The proposed algorithm will consist of speed and distance control algorithms and a combined acceleration/deceleration control law.

CHAPTER 2

BACKGROUND OF THE STUDY

In this chapter, a review of the previous literature on the different areas of research (refer to figure 4) addressed in this dissertation is given.

The literature review is organized as follows. In section 2.1, the literature on ADAS technology is summarized. Section 2.2 addresses ITS applications with concentration on CACC systems, and section 2.3 assesses the literature on traffic simulation models. Section 2.4 addresses the research in the vehicle-to-vehicle communication. Finally, an indication of the gap in the literature that will be covered in the dissertation and a statement of the research problem are presented in section 2.5 and section 2.6 respectively.

2.1 Advanced Driver Assistance Systems (ADAS)

ADAS are systems designed to assist the driver, aiming to reduce or eliminate the human error from the driving process. Brookhuis (Brookhuis, Waard et al. 2001) investigated the positive and negative impact of ADAS technology. Although ADAS has a great potential of increasing the safety and comfort for the drivers, increased complexity of the cockpit increases the likelihood of failure by the driver, or by the system itself. The acceptability of ADAS is highly dependent on the features demonstrated, and the practicality of their usage.

2.1.1 Adaptive Cruise Control

Although ACC is an ADAS technology intended for the driver's comfort and safety, it has an impact on the overall traffic flow. (VanderWerf, Shladover et al. 2003), (Zwaneveld and Arem 1997), and (Hoetink 2003) 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 (Arem, Hogema et al. 1995), 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 (Marsden, McDonald et al. 2001). (VanderWerf, Shladover et al. 2003) 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. (Kesting, Treiber et al. 2007) investigated the impact of an automated longitudinal driving control, based on the Intelligent Driver Model (IDM), on the traffic flow and dynamics. This study in particular, stated that ACC vehicles have a positive impact on traffic dynamics, even in low penetration levels. The study however, was limited only to a single lane, which fails to capture the decelerations resulting from lane changes. As ACC systems are currently limited to a small group on entry-level luxury cars, it is believed that over the next years, the ACC systems will become more widely available as the technology become more affordable and standardized.

2.2 Intelligent Transportation Systems (ITS)

The research in the field of ITS has been growing widely, especially in the United States. Recent advances in wireless communication, vehicle electronics, and artificial intelligence, allow more sophistication in the ITS applications. The research in ITS is divided into smart roads and smart cars.

2.2.1 Smart Roads

The research in the US on smart roads has been sporadic due to the lack of federal funding (Varaiya 1993). The situation has changed as the government authorities are investing more and more in ITS and smart roads.

Automated Highway Systems (AHS) were initially proposed by General Motors (GM) with sponsorship from US DOT during the late 1970s. AHS refers to a set of designated lanes on a limited access roadway where specially equipped vehicles are operated under completely automatic control (Rillings 1997). With the dramatic advancement of computers, the University of California carried out significant research and development in highway automation in its PATH (Partners for Advanced Transit and Highways) project (California 2009). The coordination of intelligent vehicles has been proposed by several researchers. (Varaiya 1993) proposed in the PATH project, a hybrid hierarchical framework, Intelligent Vehicles Highway System (IVHS), for the operation of the AHS. The study explored the challenges faced by a competent IVHS design by concluding that a socially responsive approach will require the integration of several disciplines (transportation engineering, control theory, etc) at the same time. IVHS comprises six areas of application: Traveler Information, Traffic Management, and Vehicle Control, have an extensive technical aim. The three others targeted sectors such public transportation, commercial vehicles, and rural transportation (Collier and Weiland 1994). A similar framework for vehicle communication was proposed in the DOLPHIN project (Tsugawa, Kato et al. 2000). Ritchie (Ritchie 2002) suggested a novel artificial intelligence-based solution approach to the problem of providing operator decision support in IVHS integrated highways.

2.2.2 Smart Cars

The research on smart cars was divided into 3 categories: (1) driverless cars, (2) CACC equipped vehicles, and (3) IntelliDrive equipped vehicles.

(a) Driverless Cars

Driverless cars are vehicles equipped with an autopilot system, having fully automated driving capabilities. Autonomous vehicles that are infrastructure independent are very complex to build (Benenson, Petti et al. 2008). Some motivating autonomous navigation systems considering moving obstacles and more relaxed geometric constraints were proposed by (Thrun, Bennewitz et al. 1999), (Minguez, Lamiraux et al. 2005), and (Philippsen, Jensen et al. 2006). Some work has been conducted on assessing the safety issues of such vehicles in urban environments (Thorpe, Carlson et al. 2003). (Pradalier, Hermosillo et al. 2005) presented an autonomous navigation architecture integrating moving obstacles and safety notions.

With the recent advances in autonomous driving research seen in projects such as the DARPA Grand Challenge and Google Driverless car, the introduction of driverless cars is possible in the next few years. However the public introduction on a large scale is waiting for the safety provisions and the public acceptance which is not occurring in the near future.

(b) IntelliDrive Vehicles

IntelliDrive equipped vehicles have the ability to communicate with other IntelliDrive equipped vehicles, with the infrastructure, and with wireless devices (USDOT 2010). Transportation System Operators (TSOs) are interested in IntelliDrive vehicles as traffic probes – used for the purpose of learning the state of the network. By generating real time traffic information, road networks could be significantly expanded at low costs (Dion, Robinson et al. 2010).

IntelliDrive vehicles offer a great potential to reduce or annul oscillatory shockwaves that result in traffic congestions (Arnaout, Khasawneh et al. 2010). IntelliDrive is not limited to vehicle-to-vehicle (V2V) communication. IntelliDrive uses DSRC to support V2V as well as vehicle-to-infrastructure (V2I) applications. As the potential of IntelliDrive applications is great, it is important to recognize the number of future mobility or environmental system challenges that need to be tackled before being able to use this technology efficiently. For instance, one problem that the IntelliDrive technology faces is the challenge of installing DSRC radios on the vehicles as well as installing infrastructure-based devices with which equipped vehicles would communicate (ITS-America 2010). As the technology looks very promising, the research on IntelliDrive is not expected to be completed before 2013, and that is without its actual implementation (USDOT 2010).

(c) Cooperative Adaptive Cruise Control equipped vehicles

Unlike ACC, the literature pertaining to CACC is limited. Several studies like (Shladover 2009), (Girard, Sousa et al. 2001), (Bruin, Kroon et al. 2004), and (Misener, Girard 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. Centralized and decentralized cooperative driving models in platoon formations were studied in (Halle and Chaib-draa 2005). The centralized coordination model, where the driving agent of the platoon leader coordinates other driving agents by applying strict rules, and decentralized coordination model, where the platoon is considered as a group of driving agents with a similar degree of autonomy, were compared using results from simulation scenarios that highlighted safety, time efficiency and communication efficiency aspects for each model. The centralized model was considered more efficient if the most important issue was to minimize communications and lower the autonomy of the followers, to prevent unwanted behaviors. The decentralized model was found superior if the traffic environment was unpredictable. The decentralized approach offered more flexibility since vehicles were not linked to the platoon leader, and could be used to form groups of CACC equipped vehicles. The California PATH project (Shladover 2009), described the design and implementation of a CACC system on vehicles. The research focused on the evaluation of drivers' comfort when following a lead vehicle at different CACC short range gaps controlled by an automation system, by installing four cameras recording: the face of the driver, the steering wheel, the acceleration and braking pedals, and the forward driver view. The research assessed the problem of public acceptance of the CACC technology taking into account that most drivers in the U.S. are unfamiliar even with the already available ACC systems that are currently on the market. In this study, the pilot testing provided promising results, although it appears that drivers were not willing to use the shortest gap provided by a CACC vehicle. However, the study stated that this conclusion has to be modulated by the other apparent results that the CACC testing phase was too short for participants. The success of CACC largely depends on whether or not drivers would be willing to accept the shorter following distances that could be offered by a CACC equipped vehicle (Shladover 2009).

One of the very few studies that targeted this dissertation's area of research was (VanderWerf, Shladover et al. 2003), which 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 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 shockwaves on the freeway. Another equally important study was (Arem, Driel et al. 2006), 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 (Arem, Driel et al. 2006) and (VanderWerf, Shladover et al. 2003) was very 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 penetration levels.

2.3 Traffic Simulation Models

Many of the traffic simulation packages used today are macroscopic in nature. Macroscopic models represent the traffic systems as mathematical models describing the flow of all the vehicles involved. One type of traffic modeling that deals with simulating the behavior of individual vehicles, regarded as agents, is microscopic traffic simulation (also called micro-simulation). Thus, every simulated vehicle can be seen as an individual agent having its own characteristics, and the overall traffic flow being the emergent behavior of the simulation model (A.M.Ehlert and J.M.Rothkrantz 2001). There are numerous traffic micro-simulation packages in the market (such as VISSIM, Aimsun, Corsim, etc). Although the existing traffic simulators do a tremendous job in simulating daily traffic very accurately, however, accuracy comes with great complexity. The level of details in these models comes with many model parameters (more than 45 parameters is not uncommon). This increases the model sensitivity to errors and complicates the calibration process making the model highly inflexible. Additionally, to our knowledge, no existing open-source or commercial microscopic traffic simulators that model specifically CACC vehicles and their impact on the traffic performance exist to the public.

2.4 Vehicle-to-vehicle Communication

Collecting traffic data is essential for understanding the state of the traffic network systems, analyzing the traffic flow, and taking necessary measures to reduce or avoid traffic congestions. Current methods for collecting traffic data rely on detectors that track the operating vehicles at fixed points of the highway. Such detectors include loop detectors, video cameras, acoustic radar sensors, and microwave radar sensors (Olariu and Weigle 2009). Probe-based systems are newer technologies that allow individual vehicles to report statistics, real-time, as they move through traffic (Arbabi and Weigle 2011). Automatic Vehicle Location (AVL) and Wireless Location Tracking are one of the most prominent probe-based technologies ((Olariu and Weigle 2009), (University of California ; INRIX 2010)). AVL systems are seen normally in freight vehicles used to assist in tracking the shipments and the sharing of proprietary data (Arbabi and Weigle 2010). WLT systems track the vehicles using the presence of mobile phones, relying typically on coarse-grained positioning based on cell towers. The quality of such data collection is known to be inferior because the cell towers cannot reliably identify roadways, and they track each mobile phone as a different vehicle, even though, multiple phones can be contained in a single vehicle (Arbabi and Weigle 2011).

DSRC is a general-purpose radio frequency (RF) communications link between the vehicle and the road-side infrastructure, or among vehicles (Amanna 2009). VANETs are a subclass of mobile ad hoc networks (MANETs) that consist of vehicles equipped with a special type of GPS and DSRC devices (Yousefi, Mousavi et al. 2006). VANETs can be used as a powerful tool to reduce traffic congestion and provide traffic probe-based data because of their ability to directly measure their travel time and provide accurate and real-time traffic data (Sommer and Dressler 2008).

Some studies focused on Cooperative Following (CF) which uses automated longitudinal control combined with inter-vehicle wireless communication allowing equipped vehicles to anticipate sudden and severe braking (Arem, Tampère et al. 2003). CF is an extension to the ACC functionality where the vehicles that are involved in a specific lane, transmit warnings to upstream traffic about possible shockwaves resulting from sudden decelerations. The other vehicles able to receive the warnings can anticipate the upcoming disturbance and adjust their speeds accordingly to avoid or damp the shockwave effect. The study found that in specific conditions, CF can lead to discontinuous and unstable traffic flows caused by differences in the acceleration resulted from the CF. Studies pertaining to real-time information generation and sharing were also conducted. A study (Lee, Tseng et al. 2010) proposed a wiki-like collaborative real-time traffic information generation and sharing framework involving a real-time traffic status prediction knowledge base system. The proposed methodology turns the traditional centralized data owned by the government into wiki-like distributed collective intelligence scheme. This has a potential of becoming the main stream for real-time traffic information collection and sharing scheme in the near future.

2.5 Research Gap

The related literature clearly indicates the need for more research on CACC systems and their effect on traffic dynamics. As no prior research describes a clear approach for assessing the impact of CACC systems on highways with a well-defined and practical traffic simulation model, the following conclusions can be drawn from the literature review:

1- As the ACC system can only have a slight impact on highway capacity and performance, the research must focus more on the CACC rather than the ACC technology.

2- Extensive research is needed to study the effect of CACC systems on the highway traffic dynamics in terms of flow rate, perturbations reduction, travel time spent, and average speed.

3- There is a need to develop a flexible microscopic traffic simulator that allows studying the impact of CACC equipped vehicles on the traffic performance.

This dissertation addresses those gaps and develops a flexible microscopic traffic simulator that can be used to study the effect of CACC systems on highway characteristics. Up to our knowledge, no open-source microscopic traffic simulator that studies the impact of CACC systems is available in the literature. In addition, the research gap extends to an absence of publications tackling effective CACC algorithms.

2.6 Statement of the research problem

With the occurring traffic congestions, there is a need to better manage the use of the existing infrastructure in order to make the highway system more efficient and sustainable for the twenty-first century. The approach of this study is to better manage the existing capacity rather than looking into different ways of how to increase it. With a limited highway capacity compared to the number of vehicles in operation, the small traffic jams ultimately become deadlocks resulting in bumper-to-bumper traffic.

Based on the above literature, CACC equipped vehicles offer a great potential for mitigating traffic congestions by reducing perturbations (and therefore shockwaves) and smoothening the traffic flow, and increasing the capacity on highways. Thus, it is possible to identify a two-fold problem that will provide a foundation for combating the traffic congestion problem. One problem area explores the fact that the literature on CACC is lacking. In the first part of the study, the impact of CACC vehicles on the traffic dynamics on freeways (uninterrupted flow of traffic) will be explored in different CACC penetration levels using simulation, and validate some of the findings of the very few studies done in that area. The traffic performance metrics that will be analyzed are (1) the flow, (2) the average speed, (3) the speed variation, and (4) the travel time spent. CACC is still in its early stages, thus, it is essential to study the traffic flow effects of CACC in order to assess its importance and project, if any, the problems that it might produce. The second problem area is the fact that one of the main obstacles facing CACC is that having a high level of penetration will not happen in the near future. Thus, the second attempt of this research is to find a tradeoff between driver involvement and the CACC semi-automated driving system operation. In other words, there is a need for a strategy that serves as a transition phase between a low penetration rate of CACC and a fully intelligent-vehicle-operated highway with 100% CACC equipped vehicles.

CHAPTER 3

METHODOLOGY

This chapter is dedicated to discuss the methodology utilized in the proposed dissertation research. Included in this section is a description of the research method, proposed simulation model, simulation experiments that will be conducted, model validation, and data collection procedures and analysis. Furthermore, the significance of the study, as well as the research deliverables, will be explained. The last section contains a brief justification of the limitations of the study.

The new concept being introduced is generated from previous literature, and from the research gap identified in the literature. To address the proposed problem, an agent-based microscopic traffic simulation model is developed, validated, and tested. The model is intended to characterize the dynamics of a highway system, and investigates and attempts to predict the effect of CACC-equipped vehicles on the traffic performance.

3.1 Research Method

In this research, computer simulation experiments are conducted followed by an extensive 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.

Simulation is the ideal tool for testing hypotheses, designing and redesigning systems, and making predictions, without altering the real system.

3.1.1 Why Agent-based Modeling?

Traffic systems are considered to be extremely complex systems because of the human factors and man-machine interactions. When dealing with such complexity, computer simulation is essential in order to detect behaviors that are not apparent through visual observation. As the traffic problem is regarded at as an emergent phenomenon due to the existence of phase transitions and other emergent phenomena (Vandervelde 2004), agent-based simulation is an appropriate tool to study such type of problems.

There are mainly three types of traffic simulations in the literature. (1) Microscopic - dynamic and stochastic modeling of individual vehicle movements within a system of transportation facilities; (2) Macroscopic – simulation of traffic flow, taking into consideration cumulative traffic stream characteristics and their relationships to each other; and (3) Mesoscopic – model individual vehicles at the aggregate level by speed density relationship and queuing theory approaches (Dowling, Skabardonis et al. 2004). In this study, an agent-based microscopic model of traffic is developed in order to examine the impact of having CACC embedded vehicle(s) on a multilane freeway system consisting of four lanes. The simulation type of the proposed model is a microscopic traffic simulation, modeling the behavior of individual agents on a multilane road section of a 6 km (equivalent to 3.73 miles) freeway. The approach used in the study uses macroscopic functions as well. In analyzing the individual behavior of agents in the microscopic model, macroscopic properties (like density, flow, etc) are the product of individual microscopic agents' interaction.

3.2 Simulation Model: F.A.S.T.

In this research, a microscopic agent-based traffic simulator, Flexible Agent-based Simulator of Traffic (F.A.S.T.), is developed. F.A.S.T. models the interaction of CACC equipped vehicles on a freeway and collects necessary data and statistics needed for the study (Arnaout and Bowling 2010). The object-oriented model developed using Java®, is an expansion of a preexisting open-source microscopic model originally developed by (Treiber 2010). 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 a special HOV lane (i.e. CACC accessible HOV lane). 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. Microscopic traffic simulators are the ideal simulation tools to realistically reproduce the individual flow of CACC equipped vehicles resulting in the collective flow of traffic. Microscopic traffic simulation allows capturing emergent phenomena and accurately studying the impact of CACC and ITS on traffic systems.

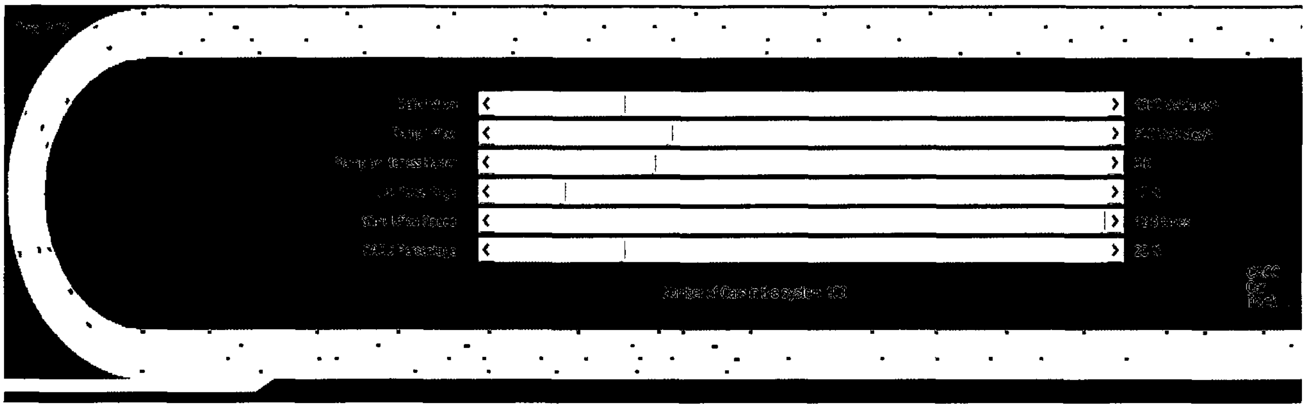


Figure 5. Snapshot of the simulation model F.A.S.T.

F.A.S.T. consists of a 6 km U-shaped freeway having four lanes, where ongoing traffic flows counterclockwise (shown in figure 5). 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 x 2 meters and for trucks is 6 x 2 meters.

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/hr 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 ramp vehicles, and the blue agents are the CACC 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/hr for cars, and between 90 and 110 km/hr for trucks, considering that the speed limit imposed on the highway studied is 100km/hr (≈ 62 mph). Drivers tend to go at increasing speeds whenever the roadway geometric characteristics are fine, regardless of the posted speed limit (Garber and Gadirau 1988).

3.2.1. Adaptive Cruise Control

CACC is an extension of ACC, with the addition of vehicle-to-vehicle communication between the equipped vehicles. Hence, before proceeding to propose the CACC algorithm, a pseudocode of a typical ACC system is presented.

ACC algorithm

V_a - ACC vehicle
O_f - front object
d(x, y) - distance from x to y
R_0 - radar range

```
use radar(R_0)
if O_f exists
   if V_a.speed > O_f.speed and d(V_c, V_f) ≤ R_0
      Decelerate (V_a, O_f)
   else
      Accelerate (V_a, O_f)
   end if
end if
```

Figure 6. Pseudocode of the ACC system

If a vehicle is ACC-equipped, it has the ability of detecting the speed and separating distance of the preceding vehicle or any other obstacle ahead. As shown in figure 6, if the speed of the ACC vehicle is smaller than the preceding object (assume as a vehicle since radars only detect objects and cannot identify if it is a vehicle or not), and if the preceding object is within the radar range of R_0, the ACC vehicle decelerates. Otherwise, the ACC vehicle accelerates to the initially set desired speed. Note that the radar range can vary in different setups and acceleration/deceleration rate can also vary based on the distance between vehicles and their estimated instantaneous speeds. For simplicity purposes, the radar range used in F.A.S.T. under ACC will be 120 meters according to (Bazzan and Klügl 2009).

3.2.2. Effective Adaptive Cruise Control (ECACC)

In this section, we introduce and describe the main three phases of a CACC algorithm, we call Effective Cooperative Adaptive Cruise Control algorithm (ECACC). The phases are: (a) CACC discovery, (b) ECACC, and (c) Acceleration and deceleration (Arnaout, Arbabi et al. 2010).

a- CACC Discovery phase (or communication phase)

Our proposed ECACC uses a standard neighbor discovery phase known in vehicular ad-hoc networks (Yan, Olariu et al. 2009). Using VANETs neighbor discovery mechanism, we extend the discovery phase appropriate for ECACC. In this phase, the ECACC equipped vehicle uses its radar to discover objects in front of it on the road. At the same time, the equipped vehicle uses DSRC beacons with standard transmission range R_1 ($R_1 \approx 300$ meters) (Transportation 2003) to transfer their location, speed, acceleration and other mobility or vehicular information. The equipped ECACC vehicle will compare the estimated location of the front vehicle discovered by the radar with the location information received from the discovered neighbors via DSRC. If there is a match on location, the equipped ECACC vehicle infers the front object as an equipped ECACC vehicle. It will send a request beacon for acknowledgement and handshaking (see figure 7). If the there is no match, the equipped vehicle treats its front vehicle as a regular non-CACC (or manual) vehicle. (H. Arbabi 2009; Arbabi and Weigle 2010) showed using Dynamic Traffic Monitoring that vehicles are capable of sharing traffic information with their neighbors in less than a millisecond, which demonstrates the efficiency of this approach.

Discover Front Vehicle

V_c - CACC vehicle
V_f - front vehicle
O_f - front object
R_0 - radar range
R_1 - DSRC range
e - acceptable error in position

```
Vc (R0,R1):
use radar(R0)
use DSRC(R1)
if Of exists
   if Vf exists
      if |Of.position - Vf.position| ≤ e
           send VANET handshaking messages
         receive Vf {position, speed, acceleration, ...}
          Vf.type = {CACC}
          return
      end if
   end if
   Vf = Of
   Vf.type = {NON-CACC}
end if
```

Figure 7. CACC Discovery Phase

b- *EACC algorithm*

The ECACC phase occurs after the CACC discovery phase described earlier. In this phase, the equipped ECACC vehicle is aware of its vehicular surrounding. The ECACC vehicle scans the preceding vehicle to determine if it is a CACC vehicle. If not, meaning that the discovered vehicle is either ACC (does not have the ability of communicating with other vehicles using VANETs) or fully manual, then the own ECACC equipped vehicle will operate as ACC and rely solely on its frontal radar. If the discovered front vehicle is also a CACC equipped vehicle, the *safety gap* g_s is calculated using the simple equation: $g_s = \textit{time gap} \times \textit{current speed}$

The time headway gap T_m of manual vehicles is in the range of 0.8 *s* (young or aggressive drivers) and 1.0 *s* (old drivers or considerate drivers) according to (Jenness, Lerner et al. 2008). The time gap T_c for CACC equipped vehicles is 0.5 *s* because of the advantage of the vehicle-to-vehicle communication according to (Arem, Driel et al. 2006) and (VanderWerf, Shladover et al. 2003). Thus, in F.A.S.T., if the vehicle is CACC equipped, T_c is set to 0.5 *s*. If the vehicle is not CACC equipped, T_m is set to a random number uniformly distributed between 0.8 *s* and 1.0 *s*.

c- *Acceleration and Deceleration*

After calculating g_s, the speeds of the ECACC vehicle and the discovered front vehicle are compared. If the speed of the ECACC vehicle is higher than the speed of the front vehicle, and the separating distance is less than equal from the calculated safety gap g_s, the ECACC equipped vehicle decelerates. Otherwise, the ECACC equipped vehicle accelerates (see figure 8) knowing the current speed and front vehicle speed, the distance among them and the calculated g_s. In this phase, the ECACC vehicle must calculate the desired acceleration or deceleration rate, as a result the speed differential *dv*, to increase or decrease its speed to the effective desired speed. Computing *dv* requires considering the current speed and speed of discovered CACC vehicle in front, the actual distance among these two vehicles and the calculated g_s. Also, shared collaborative traffic information via vehicular networks (*e.g.*, suggested maximum or minimum speed, road condition warnings, and etc.) are additional variables that are considered in computing *dv*. Note that the mechanism of acceleration and deceleration are different for each brand and model of vehicles. We assume *dv* is one of the operative inputs to the modern vehicle's electronic fuel injection kit (or voltage provider if not consuming gas) and gear ratio systems which usually control the amount of required torque and adjust the trends in speed. F.A.S.T. uses Treiber's car-following acceleration/deceleration scheme (Treiber, Hennecke et al. 2000; Treiber and Helbing 2002) for rural roads specifically for highways when the vehicles are within the time gap specified (depending on the vehicle type). In the case of CACC equipped vehicles that are farther than the headway range generated by the relative time gap, but within the range of the radar (in this case 120 *m*), the speed differential *dv* will be simply equal to: $\Delta v = v_f - v_c$. In other words, the CACC equipped vehicle will accelerate + *dv* if the front vehicle was faster (meaning that Δv is positive); or decelerate – *dv* if the front vehicle was slower (meaning that Δv is negative). This process is overridden with the IDM model as soon as the vehicles go into the time gap specified by the vehicle type. Refer to figure 8 for the algorithm.

Thus, an ECACC equipped vehicle uses its inter-vehicle communication advantage if the preceding vehicle is also CACC. Otherwise, it uses only its ACC advantage, without any vehicle-to-vehicle communication with the vehicle preceding it. Therefore, the time-gap setting of the ECACC system is set on 0.5 *s*, if it is following a CACC equipped vehicle, and on a random number uniformly distributed between 0.8 *s* and 1.0 *s* if it is following a vehicle that is not CACC equipped.

```
ECACC

Vc - CACC vehicle
Vf - discovered front vehicle
gs - safety gap
d(x, y) - distance from x to y

if Vf.type is {CACC}
   calculate gs
   if Vc.speed > Vf.speed and d(Vc, Vf) ≤ gs
      Decelerate (Vc, Vf, gs)
   else
      Accelerate (Vc, Vf, gs)
   end if
else
   use ACC
end if

Accelerate (Vc, Vf, g)

Vc - CACC vehicle
Vf - discovered front vehicle
g - safety gap
dv - |speed differential|

calculate optimal dv (Vc, Vf, g)
 Vc.speed += dv

Decelerate (Vc, Vf, g)

Vc - CACC vehicle
Vf - discovered front vehicle
g - safety gap
dv - |speed differential|

calculate optimal dv (Vc, Vf, g)
 Vc.speed -= dv
```

Figure 8. Pseudocode of the CACC system

3.3 Model Validity

When building microscopic traffic simulation models, the main question is how to take into account the humans aspect of driving and model their behavior realistically. Thus, the proposed model, in order to be valid, must take into consideration previously validated traffic sub-models that describe the behavior of the agents effectively.

3.3.1 Car following model

The longitudinal section of F.A.S.T., concerned strictly with acceleration and braking deceleration of the drivers, uses the "Intelligent Driver Model" (IDM) developed by (Treiber, Hennecke et al. 2000) as a car-following model. The IDM guarantees crash-free driving and has been previously validated in the literature as a competent car following model. In IDM, the acceleration of each operating vehicle is a continuous function of the velocity v_t, the separating gap s_t, and the velocity difference (while approaching the preceding vehicle) Δv_t. The acceleration equation of the IDM model is presented below:

$$\dot{v}_t = a\left[1 - \left(\frac{v_t}{v_0}\right)^4 - \left(\frac{s^*(v_t, \Delta v_t)}{s_t}\right)^2\right] \quad (1)$$

Where:

a is the initial acceleration, or maximum attained acceleration on a free road,

v_t is the current velocity of the vehicle,

v_0 is the desired velocity, dependant on the vehicle's desired speed preference,

s^* is the desired separating distance between the two vehicles, dependant on the vehicle's desired gap preference,

s is the actual separating distance between the two vehicles.

The decision of any agent to accelerate depends on its current speed, on the speed of the preceding agent ahead of him, the speed difference, and on the distance between the two agents. The acceleration is affected by the agent's desired acceleration $\left(\frac{v_t}{v_0}\right)^4$ and the braking deceleration induced by the preceding agent which reduces the separating distance $\left(\frac{s^*(v_t, \Delta v_t)}{s_t}\right)^2$.

The deceleration equation of the IDM model is presented below:

$$s^*(v, \Delta v) = s_0 + vT + \frac{v \Delta v}{2\sqrt{ab}} \qquad (2)$$

Where:

v is the current velocity of the vehicle,

Δv is the velocity difference of the two vehicles,

s0 is the minimum bumper-to-bumper distance,

vT is the desired safety time headway when following other vehicles,

a is the acceleration in everyday traffic,

b is the comfortable deceleration in everyday traffic.

Therefore, the model used in F.A.S.T. uses the following equation to update the velocity of the vehicles throughout the simulation:

$$\boxed{v_{t+1} = v_t + \Delta v_t} \qquad (3)$$

Where:

v_{t+1} is the velocity of the vehicle at time t+1,

v_t is the current velocity of the vehicle,

Δv_t is the velocity difference of the same vehicle at t and t+1.

As mentioned earlier, the initial vehicles' time headway gap will range between 0.8s (younger/aggressive drivers) and 1.0 (older/considerate drivers) according to (Jenness, Lerner et al. 2008), to allow more variability in the driving behavioral patterns among drivers, thus making the model less deterministic (the values are pseudo-random with a uniform distribution in the range specified). Furthermore, the maximum desired speed will also be chosen from a uniform distribution between 100km/hr and 120km/hr (for cars) and 90km/hr and 110km/hr (for trucks), for the same reasons.

3.3.2 Lane changing model

Unlike the IDM car-following model, lane changing decisions depend on all neighboring agents, and not solely on the immediate agent ahead. The lateral section of F.A.S.T., concerned with overtaking and weaving, uses the car-following lane-change model *Minimizing Overall Braking Induced by Lane change* (MOBIL) proposed by (Kesting, Treiber et al. 2002). In MOBIL, lane change takes place if the potential new target lane is more beneficial to the agent performing the lane change (referred to as incentive criterion), and if the lane change can be performed safely (referred to as safety criterion). The incentive criterion is assessed by weighing the advantage gained by the agent performing the lane change on the target lane. This is measured by the increased acceleration or reduced braking deceleration by the own agent (advantage for the agent performing the lane change) against the decreased acceleration or increased braking deceleration (disadvantage for the other agents) for the other agents. The disadvantage imposed on the other agents is weighted with a politeness factor p that determines to which degree the agents performing the lane change influence the lane-changing decision. The following incentive criterion is required for a lane-changing decision:

$$acc'(M') - acc(M) > p\,[\,acc(B) + acc(B') - acc'(B) - acc'(B')\,] + a_{thr} \quad (4)$$

Where:

acc is the actual acceleration generated from the IDM model,

acc' is the acceleration after a possible lane change,

M is the agent label before performing the lane change,

M' is the agent label after performing the lane change,

B is the following agent on the target lane before the lane change,

B' is the following agent on the target lane after the lane change,

a_{thr} is a lane changing threshold.

The advantage is measured by comparing the own agent advantage: $acc'(M') - acc(M)$ with the combined disadvantage on the other agents: $p\,[acc(B) + acc(B') - acc'(B) - acc'(B')] + a_{thr}$.

Note that because of the egoistic nature of drivers, the politeness factor p is always less than 1.

The safety criterion is formulated in terms of longitudinal accelerations using the information provided by the longitudinal car-following model IDM. This safety criterion guarantees that after the lane change, the deceleration of the successor *acc' (B')* in the target lane does not exceed a given safe limit b_{safe} using the following formula:

$$acc'(B') > -b_{safe} \tag{5}$$

Where:

acc' is the actual acceleration after a possible lane change,

B' is the following agent on the target lane after the lane change,

b_{safe} is the maximum safe deceleration that must be lower than the maximum deceleration.

Using this approach, in order to perform a lane change safely, larger gaps between the following agent in the target lane and the own agent position are required. If the following agent is going slower, lower values for the gap are allowed. Using this safety criterion, crashes due to lane changes are not possible in F.A.S.T. In F.A.S.T., in order for an agent to perform a lane change, both the safety criterion and the incentive criterion must be satisfied.

3.3.3 Verification and Validation

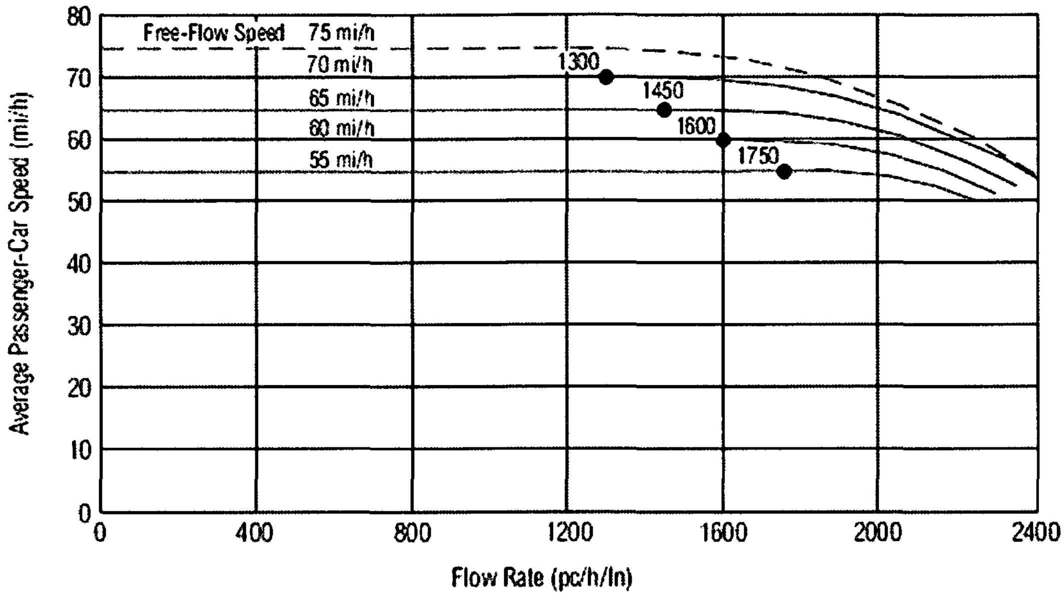
In order to verify and validate the proposed traffic model, the traffic data generated by the model was compared to historical data taken from the Highway Capacity Manual. According to the Highway Capacity Manual, at a speed limit of 60 mph, the average flow rate in a multilane highway is around 2200 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 (taken from the Highway Capacity Manual, Dec 2000)

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

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. Graph 1 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.



Graph 1. Speed-Flow Curves for multilane highway sections (taken from the Highway Capacity Manual, Dec 2000, Exhibit 21-3, pg. 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 vehicles/hr. Five replications of each arrival rate were conducted. Figure 9 shows the speed-flow curve generated from the proposed model.

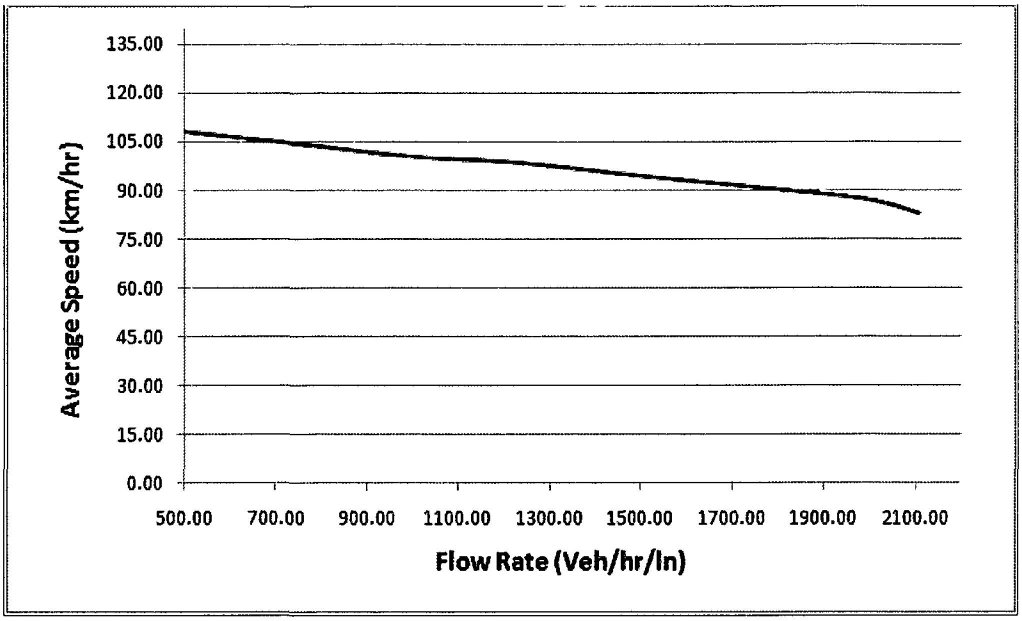


Figure 9. Speed-Flow Curves in the simulation model

The curve in both graph 1 and figure 9 are very similar in behavior. As observed, the speed increases until reaching a certain maximum capacity and after that it starts decreasing. Note that after the maximum capacity is reached, as the average speed is dropping the flow rate starts dropping as well in a behavior similar to the one shown in figure 10.

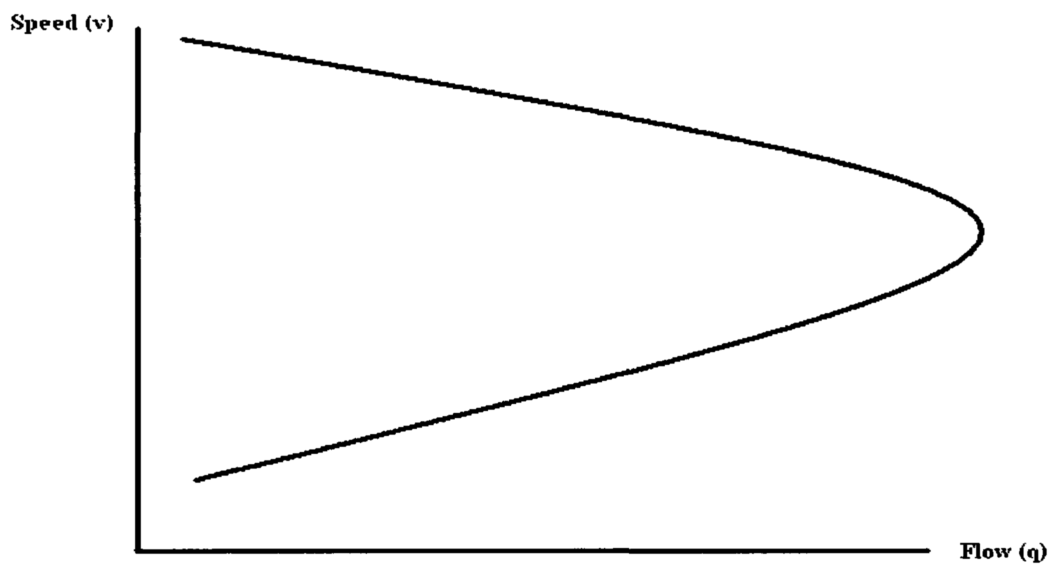


Figure 10. Speed – Flow relationship (fundamental speed-flow diagram)

3.4 Hypotheses

Based on the literature noted earlier in this proposal, two major hypotheses areas guided the analysis of data. The primary claim that was tested in order to validate this research is whether using CACC systems will be useful in enhancing traffic performance through traffic networks. To this end, specific research hypotheses have been developed, that aim to answer these underlying questions.

Two main hypotheses were tested, these include:

Hypothesis 1:

H0: There is no significant difference in traffic performance metrics using CACC vehicles on freeways with different penetration levels compared to not using CACC vehicles.

H1: There is a significant difference in traffic performance metrics using CACC vehicles on freeways with different penetration levels compared to not using CACC vehicles.

Hypothesis 2:

H0: There is no significant difference in traffic performance metrics using CACC vehicles, given priority access to special HOV lanes, at low penetration levels compared to not using CACC vehicles.

H1: There is a significant difference in traffic performance metrics using CACC vehicles, given priority access to special HOV lanes, at low penetration levels compared to not using CACC vehicles.

For both hypotheses, various sensitivity experiments were conducted, in which the percentage of the CACC-equipped vehicles increases. Analysis of variance (ANOVA) was used to test whether the means of the performance metrics compared in different scenarios were significantly different from each other. As ANOVA shows if the differences between the different scenarios are significant or not, it is followed by post hoc analyses to identify the impact of CACC compared to the base case and also among the different CACC market penetration levels. Dunnett T3 Post hoc was chosen because the test assumes unequal variances. In other words, it is a more conservative post hoc analysis and therefore if it shows significance then there is "probably" an actual significance between the groups being compared. Regression analysis was also conducted to study whether the value of the performance metrics on the proposed differed from the values on other significantly. From these experiments, it would be clearer to the researchers if the CACC system shows significant improvements to the traffic performance, and would allow the researchers to make predictions on the efficacy of the system being studied.

3.5 Data Collection and Analysis

F.A.S.T. is a traffic simulator that models realistically both the macro dynamics of traffic flow and the individual driving behaviors of drivers. More specifically, F.A.S.T collects macroscopic measures that result from the microscopic properties of the model. Hence, four performance metrics will be collected to analyze the simulations.

Performance Metric	Collection Method
Average Speed	Averaging the speed of all agents passing through a specified fixed point acting as a loop detector.
Average Time Spent	Creating an entry point and an exit point on the freeway and recording these times for each agent, then averaging the difference.
Flow	Getting the throughput of the exiting agents – creating a counter that tracks the number of agents passing through the system. Every 5-min, the updated counter is subtracted from the previous counter
Variation of the speed	Standard deviation calculated from the average speed using the standard deviation and variance formulas

Table 2. Performance metrics and collection methods

As shown in table 2, the average speed was collected by averaging the speed of all the vehicles passing by a specified point acting as a loop detector. The point was placed at 100 meters before the on ramp. The average time spent was collected by creating an entry point and an exit point on the freeway, and calculating the travel time before the vehicles exit the system. The rate of flow was calculated by getting the throughput of the exiting vehicles. Note that the exit point for the agents was collected at a distance of 2650 meters, at 100 meters before the ramp. The reason being is to catch the effects of the ramp on the traffic performance. For the rate of flow, just as suggested by the 1985 Highway Capacity Manual (HCM 1985), 5-min was used as the interval of flow asserting that this measurement range is sufficient and does not affect the accuracy of the results. Lastly, the standard deviation and variance of the speed were calculated for studying variation of the speed from the average speed using their relative formulas. In the proposed study, the main focus was on the flow rate and average speed performance metrics. Note that the density, although an important performance indicator of traffic, was not collected (or more accurately collected but not analyzed) because it is used to calculate the Level of Service (LOS) of highways and other measures that are out of scope of this study.

The main concept associated with the research proposed is that implementing CACC-equipped vehicles will impact the traffic dynamics on freeways positively. While this system shows promise, it is years away from actual implementation. Even with successful implementation of the system, reaching a high CACC penetration levels on freeways is an incremental strategy that would take years. Therefore, statistical analysis must be performed to determine, (1) the efficacy of the CACC system at different penetration levels, and (2) the efficacy of the CACC system when it is deployed incrementally, at lower penetration levels.

Note that the model is ran for a warm-up period of 5 minutes in every replication in order to reduce the noise in the data and obtain more accurate results by allowing the system to reach a steady state.

3.6 Significance of the Study

The significance of the innovative ideas proposed in this research is as follows:

1. Provide a platform (agent-based microscopic traffic simulator) in which any CACC algorithm (current or future) may be evaluated.
2. Provide detailed analysis associated with implementation of CACC vehicles on freeways.
3. Investigate a progressive deployment strategy for CACC on freeways, by giving CACC vehicles access to special lanes.

3.7 Deliverables of the Research

It is envisioned that the research proposed will provide the following deliverables:

1. A fully functional agent-based microscopic traffic simulation model (F.A.S.T.),
2. A pseudocode of an Effective Cooperative Adaptive Cruise Control (ECACC) algorithm,
3. A report detailing results and recommendations of research, and
4. A detailed analysis of various performance measures pertaining to CACC systems.

3.8 Limitations

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.

The ramp that is discussed in the first and second phase of the experiments, have been designed in a “collision free” manner for simplicity purposes. However in doing so, the behavior of the ramp is not as realistic as a real physical ramp because in F.A.S.T., the vehicles wait for a safe gap and merge on the freeway. This sudden merging of several vehicles creates the severe perturbations that are observed in the model. In real life, the vehicles rarely have to stop and merge incrementally (causing more risk of having an accident) and create gradual perturbations that are less severe than the ones observed in the proposed model.

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.

CHAPTER 4

EXPERIMENTS AND RESULTS

Following the previous literature about ACC and CACC designs ((Bruin, Kroon et al. 2004), (Naus, Vugts et al. 2010), and (Kesting, Treiber et al. 2007)), and the algorithm described in the chapter three, 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 vehicle, 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 (oversaturated) can lead to congestion on the freeway, while a low traffic scenario (under saturated) 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 4000 veh/hr and 5000 veh/hr 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/hr and the 8000 veh/hr (where severe jams were observed). At 6000 veh/hr, a stop-and-go traffic is observed with minor traffic congestion occurrences. The politeness factor of vehicles in lane changing was set to 0.2 (for cars and trucks) and in merging (i.e. merging from a ramp to the freeway) was set to 0.

The experiments were divided into three phases:

4.1 Phase 1: On-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 11 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).

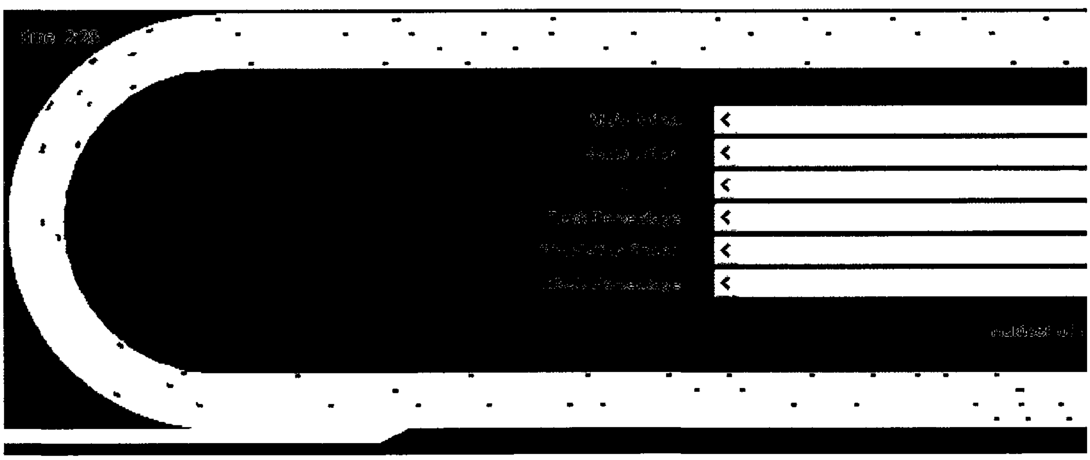


Figure 11. Snapshot of F.A.S.T. in phase 1

To ensure statistical validity, 30 stochastically independent simulations were performed for each selected scenario. Having a total of 30 scenarios (six different penetration rates and five different arrival rates), the simulations were ran for 90 minutes per each replication. Note that a 100% CACC penetration scenario is in fact lower than a complete 100% CACC equipped highway, due to the 10% penetration of trucks that is constant (trucks cannot be CACC equipped in this study). In other words, a 100% CACC scenario only means that 90% of the total agents in the system are cars (where all of them are CACC equipped) and the remaining 10% are non-CACC equipped trucks.

4.1.1 Flow rate analysis (phase 1)

Figure 12 shows the rate of flow in different CACC penetration levels and different arrival rates.

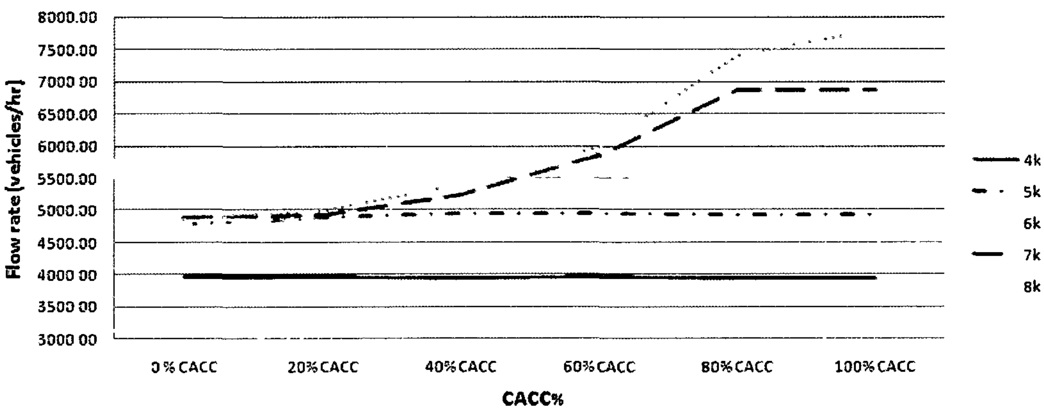


Figure 12. Flow rate analysis (phase 1)

Observing figure 12, for the 4000 veh/hr arrival rate scenario, 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 is not observed 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 increase in the flow rate is observed. In the highest arrival rate scenario (i.e. 8000 vehicles/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. The rate of flow is relatively smaller than the flow observed when validating the model in section 3.3.3 (chapter 3) because of the negative effect of the on-ramp on the traffic performance. Analysis of variance (ANOVA) was used to test whether the means of the flow in the different scenarios were significantly different from each other having 0% CACC scenario as the reference case. Starting with the rate of flow in the 4000 veh/hr scenario, although some significance was found ($p = 0.036$), after conducting a Dunnett T3 Post hoc analysis, the difference was not significant when comparing the 0% CACC scenario with the other scenarios. For instance, the statistical difference between a 0% CACC penetration scenario and a 100% CACC penetration resulted in a $p = 0.007$. However, that significance was due to a very low standard error since the mean difference was only 15.37 (agents or vehicles) barely greater than the standard error. Thus in this scenario, we considered the difference in the flow rates at different CACC penetration as non significant. A screenshot of the detailed results taken from SPSS, a statistical software used in this research, were shown in table 3.

flow
Dunnett T3

(I) CACC %	(J) CACC %	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
0%	20%	.02200	3.09834	1.000	-9.4471	9.4911
	40%	13.02867	9.00405	.894	-15.1772	41.2345
	60%	3.38167	2.85432	.977	-5.4081	12.1714
	80%	9.93367	4.45223	.349	-3.6988	23.5662
	100%	15.37800*	4.15077	.007	2.6992	28.0568
20%	0%	-.02200	3.09834	1.000	-9.4911	9.4471
	40%	13.00667	8.84300	.882	-14.8253	40.8387
	60%	3.35967	2.29629	.892	-3.6544	10.3738
	80%	9.91167	4.11681	.252	-2.8068	22.6301
	100%	15.35600*	3.78876	.003	3.6885	27.0235
40%	0%	-13.02867	9.00405	.894	-41.2345	15.1772
	20%	-13.00667	8.84300	.882	-40.8387	14.8253
	60%	-9.64700	8.76049	.986	-37.2927	17.9987
	80%	-3.09500	9.40326	1.000	-32.2786	26.0886
	100%	2.34933	9.26434	1.000	-26.4865	31.1851
60%	0%	-3.38167	2.85432	.977	-12.1714	5.4081
	20%	-3.35967	2.29629	.892	-10.3738	3.6544
	40%	9.64700	8.76049	.986	-17.9987	37.2927
	80%	6.55200	3.93644	.770	-5.7074	18.8114
	100%	11.99633*	3.59196	.027	.8416	23.1510
80%	0%	-9.93367	4.45223	.349	-23.5662	3.6988
	20%	-9.91167	4.11681	.252	-22.6301	2.8068
	40%	3.09500	9.40326	1.000	-26.0886	32.2786
	60%	-6.55200	3.93644	.770	-18.8114	5.7074
	100%	5.44433	4.95755	.989	-9.6601	20.5487
100%	0%	-15.37800*	4.15077	.007	-28.0568	-2.6992
	20%	-15.35600*	3.78876	.003	-27.0235	-3.6885
	40%	-2.34933	9.26434	1.000	-31.1851	26.4865
	60%	-11.99633*	3.59196	.027	-23.1510	-.8416
	80%	-5.44433	4.95755	.989	-20.5487	9.6601

*. The mean difference is significant at the 0.05 level.

Table 3. Dunnett T3 results at 4000 veh/hr arrival rate (screenshot taken from SPSS)

In the 5000 veh/hr scenario, the results were barely significant. After conducting a Dunnett T3 Post hoc analysis on the results of the 5000 veh/hr scenario, although an increase in the flow was observed in all the CACC penetration levels compared to the base case of 0% CACC, the mean difference was always less than 162 vehicles. Therefore, same as the 4000 veh/hr case, the CACC penetration at 5000 veh/hr was considered to be non significant. After conducting a Dunnett T3 Post hoc analysis on the 6000 vehicles/hr scenario, it was shown that any level of CACC penetration is beneficial to the system. However, there was an optimal level (at 60% CACC) where after that the effect of CACC started to become non significant (which also validates the results of a previous study (Arnaout and Bowling 2010) pertaining to the CACC sensitivity to the arrival rate). Table 4 shows the Dunnett T3 Post hoc test results on 6000 veh/hr. The penetration level (i) and (j) are the CACC penetration levels being compared together. Sig. is the significance of the results compared.

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑*	0.003
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.000
40%	60%↑	0.000
60%	80%↑	1.000
80%	100%↑	1.000

Table 4. Flow rate: Dunnett T3 Post hoc on 6000 veh/hr (phase 1)

* The arrows refer to an increase/decrease in the results of the 2nd column compared to the first column.

In the 7000 veh/hr and 8000 veh/hr scenarios, the results were more linear and easier to analyze. The flow rate was proportional to the arrival rate and to the penetration rate of CACC vehicles. In the 7000 veh/hr scenario, although all the CACC penetration levels had a positive effect on the flow rate, the transition between 0% CACC to 20% CACC was not statistically significant. In addition, the transition from 80% CACC to 100% CACC was also not significant (refer to table 5).

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.999
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.000
40%	60%↑	0.000
60%	80%↑	0.000
80%	100%↑	1.000

Table 5. Flow rate: Dunnett T3 Post hoc on 7000 veh/hr (phase 1)

In the 8000 veh/hr scenario, all the penetration levels were positively significant except for the transition between 0% CACC and 20% CACC where the results were positive but not statistically significant (refer to table 6).

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.947
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.016
40%	60%↑	0.000
60%	80%↑	0.000
80%	100%↑	0.000

Table 6. Flow rate: Dunnett T3 Post hoc on 8000 veh/hr (phase 1)

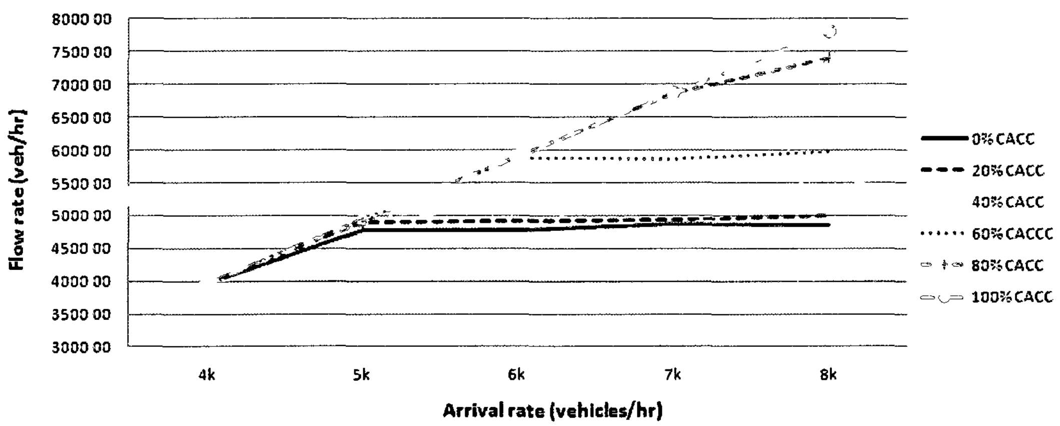


Figure 13. Effect of CACC system on the flow rate (phase 1)

Another way to observe the effect of CACC on the flow rate is shown in figure 13. The effect of CACC is minor at low arrival rates but tends to increase exponentially in higher arrival rates, especially in higher CACC penetrations. The decrease of flow rate is observed in the case of lower CACC penetration and higher arrival rates (i.e. 7k and 8k). However, the flow rate is proportional to the increase in the arrival rate in the cases of higher CACC penetrations (> 60% CACC). Note that in several other studies, the arrival rate is replaced by time of the day, when peak hours could represent the high arrival rate of vehicles on the highway. To avoid confusion, this study compared the flow rate with the arrival rate where a lowest arrival rate represents a low to moderately saturated traffic (no major traffic congestions), and the highest arrival rate represents an oversaturated highway (with severe congestion occurances).

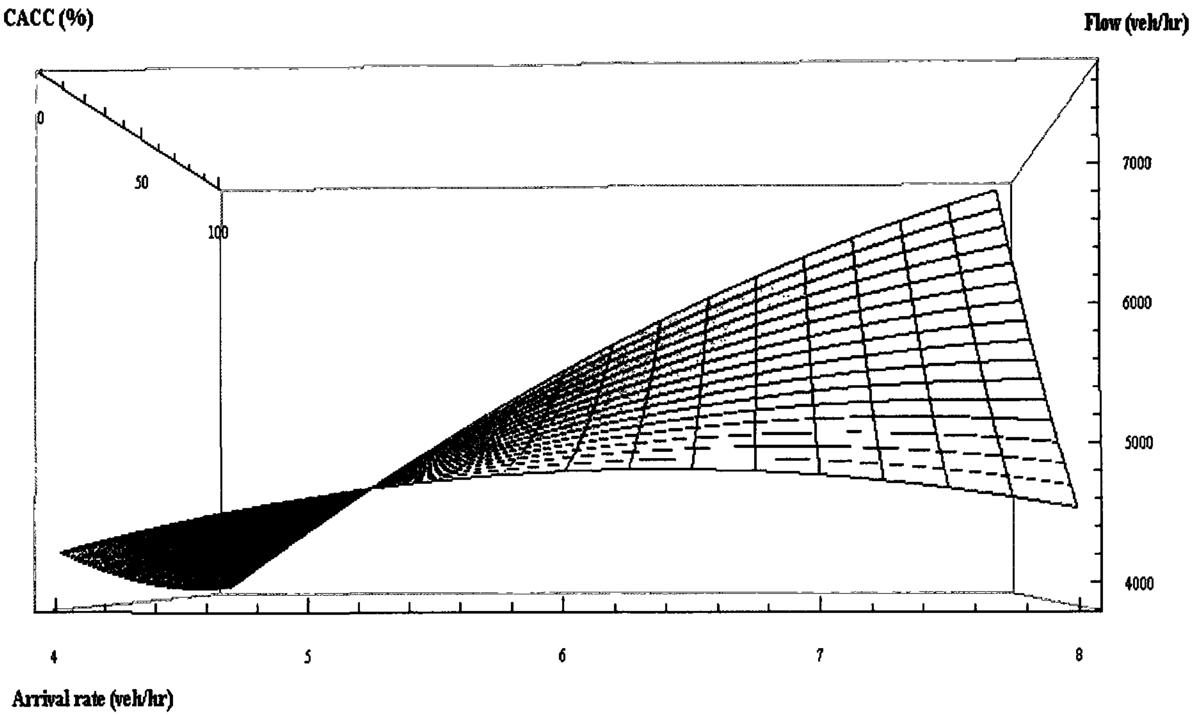
It was concluded from the results of 4000 veh/hr, 5000 veh/hr, and 6000 veh/hr that the effect of CACC on the traffic flow rate in low traffic hours (or low arrival rates) is minimal because the traffic flow is already running in free flow conditions. However, the impact of CACC is maximal in high traffic 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%).

A statistical regression analysis was conducted to understand how the independent variables affect the dependent variable in the system. In this case, the independent variables are the CACC penetration rates (the multiples of 20% including the 0% CACC). The dependant variable is the flow rate that gets affected by the change of the CACC penetration levels. Regression analysis is a forecasting tool, widely used to predict models and deduce causal relationship between the independent and dependent variables. After running a sequential quadratic programming regression analysis, the optimal solution was found. The model equation generated is:

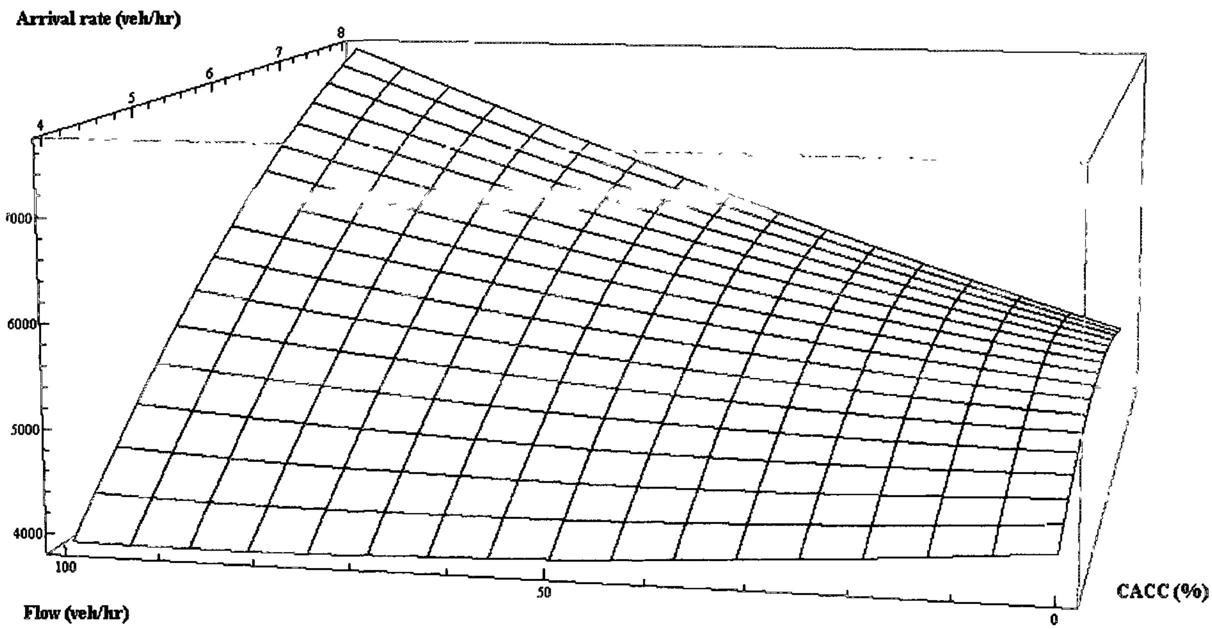
$$\mathbf{Z_1 = 529.55 + 1348.38\, \textit{ar} - 43.01\, \textit{pr} + 8.7\, \textit{ar} * \textit{pr} - 105.99\, \textit{ar}\ \text{^}2 + 0.047\, \textit{pr}\ \text{^}2} \qquad (6)$$

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

To measure the variability of the flow in the predicted model, the r-squared was calculated. The very high resulted r-squared, 0.92, indicates a very good fit. Additionally, graph 2 and graph 3 show the traffic flow in all the scenarios studied according to the generated model equation, in 3D. In graph 2, a slight increase in flow is observed proportional to the arrival rate until reaching a critical point around 6500 veh/hr arrival rate, where the flow becomes constant, then eventually starts to decrease. The flow at this arrival rate was 4877.16 veh/hr for four lanes (or 1219.29 veh/hr/ln) and is the maximum flow attainable by the highway (having a ramp) without the presence of CACC vehicles. At higher arrival rates, this flow will eventually tend to decrease as shown on the graph. The CACC penetration does not affect the flow rate significantly in low arrival rates as shown in graph 3. The exponential increase of the flow rate is observed in graph 3 at high traffic arrival rates (7000 veh/hr and 8000 veh/hr) and reaches its highest capacity of 7806.74 veh/hr (per four lanes) or 1951.68 veh/hr/ln showing that the flow of the traffic is directly proportional to the CACC market penetration and the arrival rate.



Graph 2. 3D graph of the traffic flow of the generated model - snapshot 1 (phase 1)



Graph 3. 3D graph of the traffic flow of the generated model - snapshot 2 (phase 1)

4.1.2 Time spent analysis (phase 1)

The time spent by the agents to traverse the system was also studied as a performance metric for the traffic performance. Figure 14 shows the average time spent by the vehicles on the 6 km highway in different arrival rates and CACC penetration levels.

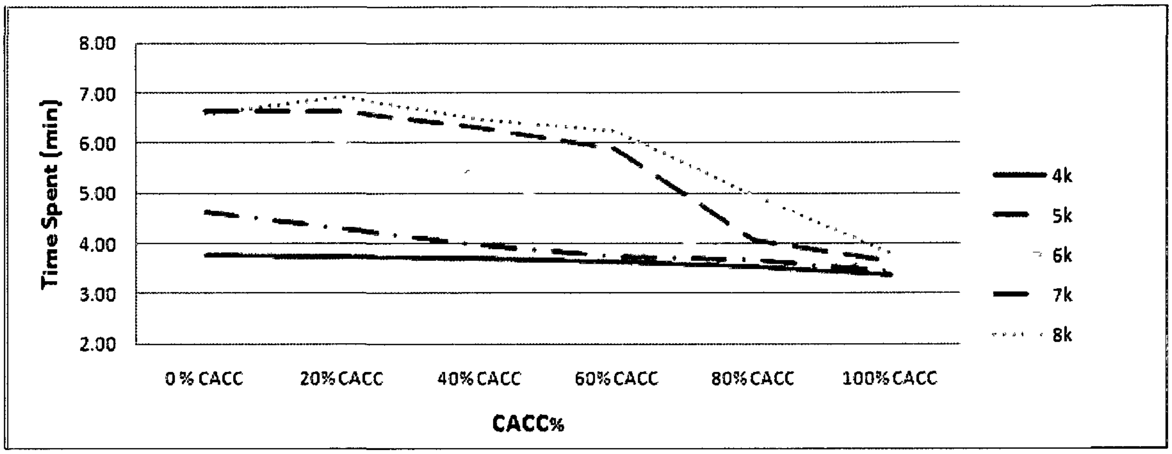


Figure 14. Time spent analysis (phase 1)

The benefit of the CACC system is more observed in higher arrival rates (especially in 7000 veh/hr and 8000 veh/hr where congestions occurred) and higher CACC penetration rates. To analyze the difference, ANOVA was performed. At the lowest arrival rate (i.e. 4000 veh/hr), there was a slight decrease in the time spent between different CACC penetration levels but the differences were not statistically significant. To be precise, some significance was observed at higher CACC rates (60%, 80%, and 100%) however, that significance was due to a very low standard error (the mean difference was only .13 minutes for the 60%, .21 minutes for the 80% and .39 for the 100%). Refer to table 7 for the Dunnett T3 Post hoc results.

Multiple Comparisons

time
Dunnett T3

(I) CACC %	(J) CACC %	Mean Difference (I-J)	Std Error	Sig	95% Confidence Interval Lower Bound	Upper Bound
0%	20%	31033	12545	213	- 0735	6942
	40%	66100*	10658	000	3268	9952
	60%	85333*	10352	000	5261	1 1806
	80%	92800*	10415	000	5993	1 2567
	100%	1 15567*	10754	000	8192	1 4922
20%	0%	- 31033	12545	213	- 6942	0735
	40%	35067*	07709	001	1108	5905
	60%	54300*	07280	000	3133	7727
	80%	61767*	07369	000	3860	8494
	100%	84533*	07841	000	6022	1 0885
40%	0%	- 66100*	10658	000	- 9952	- 3268
	20%	- 35067*	07709	001	- 5905	- 1108
	60%	19233*	03038	000	0980	2866
	80%	26700*	03245	000	1672	3668
	100%	49467*	04208	000	3664	6229
60%	0%	- 85333*	10352	000	-1 1806	- 5261
	20%	- 54300*	07280	000	- 7727	- 3133
	40%	- 19233*	03038	000	- 2866	- 0980
	80%	07467*	02026	008	0127	1366
	100%	30233*	03359	000	1977	4069
80%	0%	- 92800*	10415	000	-1 2567	- 5993
	20%	- 61767*	07369	000	- 8494	- 3860
	40%	- 26700*	03245	000	- 3668	- 1672
	60%	- 07467*	02026	008	- 1366	- 0127
	100%	22767*	03548	000	1182	3371
100%	0%	-1 15567*	10754	000	-1 4922	- 8192
	20%	- 84533*	07841	000	-1 0885	- 6022
	40%	- 49467*	04208	000	- 6229	- 3664
	60%	- 30233*	03359	000	- 4069	- 1977
	80%	- 22767*	03548	000	- 3371	- 1182

* The mean difference is significant at the 0 05 level

Table 7. Time Spent: Dunnett T3 Post hoc on 4000 veh/hr (screenshot taken from SPSS)

At 5000 veh/hr, statistical significance was observed in the 40% CACC and higher. At 20% CACC the differences in the means were not statistically significant (refer to table 8 for the Post hoc results). The same behavior was observed in the arrival rate of 6000 veh/hr. At 20% CACC no statistical significance was observed. At 40% CACC and higher, the results were significant.

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.213
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.001
40%	60%↑	0.000
60%	80%↑	0.008
80%	100%↑	0.000

Table 8. Time Spent: Dunnett T3 Post hoc on 5000 veh/hr (phase 1)

At 7000 veh/hr, the results were significant at 60% CACC and higher. At 20% CACC and 40% CACC the difference compared to the base case of 0% CACC were not statistically significant ($p = 1.0$ and $p = 0.619$ for 20% and 40% respectively). At 8000 veh/hr, the results were significant at 80% CACC and higher. In lower CACC levels, the differences were not statistically significant (refer to table 9 for the Post hoc results).

Note that the arrow pointing down in the tables of this analysis means that the penetration level (j) had a negative effect or more accurately, the time spent in the system in the scenario with penetration level (j) was longer than the time spent in the system in the scenario with penetration level (i).

Penetration level (i)	**Penetration level (j)**	**Sig.**
0%	20%↓	0.961
0%	40%↓	1.000
0%	60%↑	0.990
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.232
40%	60%↑	0.988
60%	80%↑	0.000
80%	100%↑	0.000

Table 9. Time Spent: Dunnett T3 Post hoc on 8000 veh/hr (phase 1)

Thus, the conclusion is that CACC usage is beneficial in terms of reducing the time spent by the vehicles, however, its effect is very sensitive to the market penetration as well as the arrival rate of the vehicles. Significant improvements were observed at high arrival rates and high CACC market penetration.

4.1.3 Average Speed analysis (phase 1)

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 15 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, at the arrival rate of 4000 veh/hr, statistical significance was found in all the cases except the transition between 0% CACC and 20% CACC where the effect of CACC was positive but not significant (refer to table 10).

Penetration level (i)	**Penetration level (j)**	**Sig.**
0%	20%↑	0.789
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.000
40%	60%↑	0.024
60%	80%↑	0.002
80%	100%↑	0.00

Table 10. Average speed: Dunnett T3 Post hoc on 4000 veh/hr (phase 1)

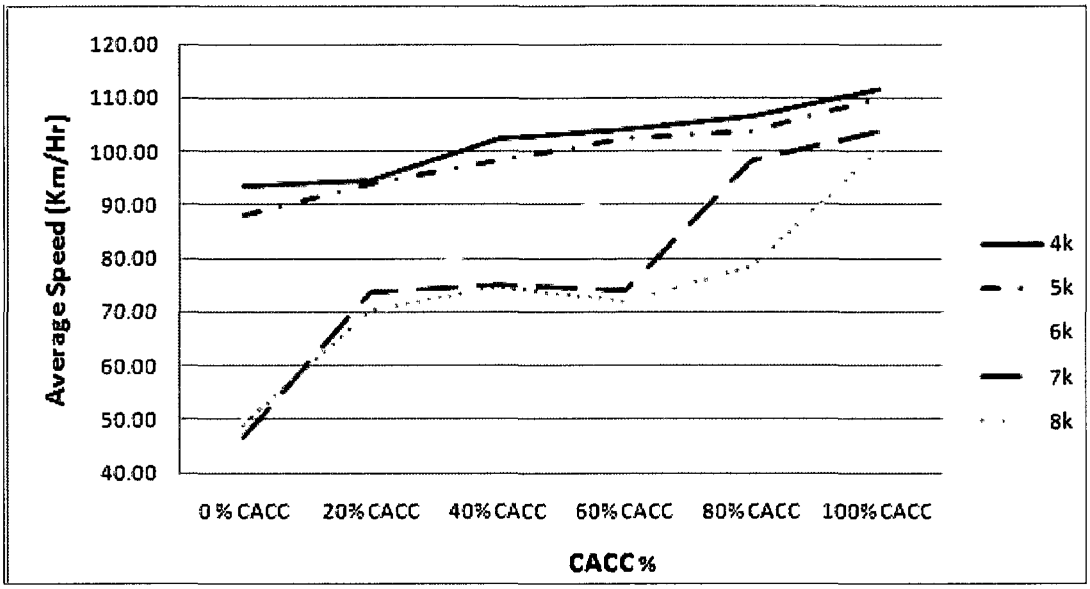


Figure 15. Average speed analysis (phase 1)

At 5000 veh/hr the effect of CACC was positive in all the cases. All the penetration rates showed significance except the transition between 60% CACC and 80% CACC where the results were positive but not significant with a p= 0.381 (refer to table 11 for the Post hoc test results).

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.000
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.037
40%	60%↑	0.000
60%	80%↑	0.381
80%	100%↑	0.000

Table 11. Average speed: Dunnett T3 Post hoc on 5000 veh/hr (phase 1)

At 6000 veh/hr the effect of CACC was positive and statistically significant in all the cases compared to the base case of 0% CACC. At 7000 veh/hr and 8000 veh/hr the behavior of the average speed changed and was no longer linear. At 7000 veh/hr, from 0% CACC to 40% CACC the increase in speed was proportional to the CACC penetration and the results showed positive significance. However, between 40% CACC and 60% CACC, the speed was reduced but with no statistical significance (refer to table 12). Then, the speed increased proportionally with the CACC penetration rate. As the only drop in speed (that was not proportional with the CACC penetration) was not significant, we concluded that at 7000 veh/hr, the overall effect of CACC is proportional to the increase in the average speed detected by the speed loop detector.

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.000
0%	40%↑	0.001
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.975
40%	60%↓	0.980
60%	80%↑	0.000
80%	100%↑	0.000

Table 12. Average speed: Dunnett T3 Post hoc on 7000 veh/hr (phase 1)

A similar non perfectly linear behavior was observed in the arrival rate of 8000 veh/hr. As the CACC penetration increased, the average speed increased until 40% CACC where it dropped slightly (at the 60% CACC) then increased again. However, the drop in speed was not statistically significant. The CACC penetrations were all significant compared to the base case; however, comparing the increase of the CACC penetration levels between each multiple was not significant in the cases of 20% CACC to 40% CACC and from 40% CACC to 60% CACC (refer to table 13 for the results of the Dunnett T3 Post hoc test).

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.000
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.981
40%	60%↓	0.998
60%	80%↑	0.000
80%	100%↑	0.000

Table 13. Average speed: Dunnett T3 Post hoc on 8000 veh/hr (phase 1)

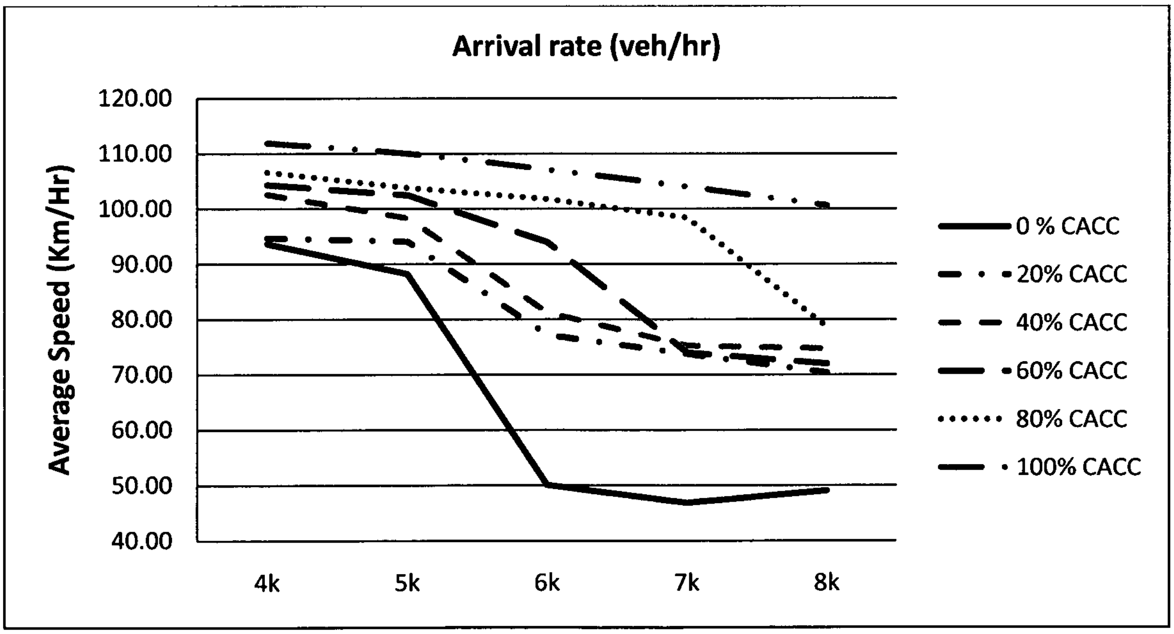


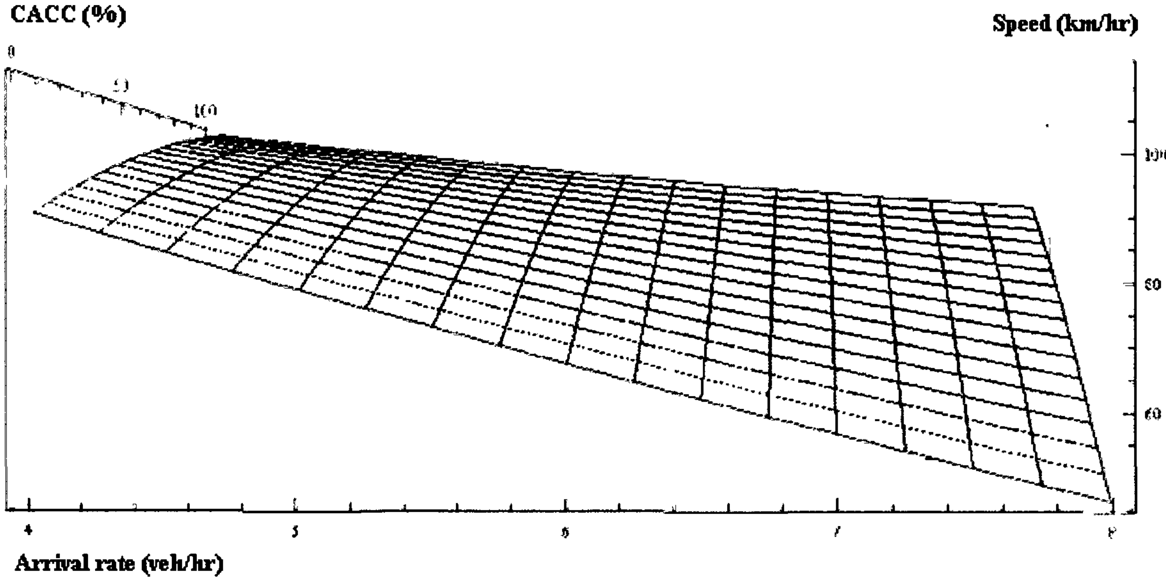
Figure 16. Effect of CACC system on the average speed (phase 1)

A clearer way to observe the effect of CACC system on the average speed of the vehicles is shown in figure 16. As all the speeds at different CACC penetration levels tend to decrease, it is observed that with higher CACC penetration the average speed (even though it is decreasing) is much higher than scenarios with lower CACC penetration. For instance, at 0% CACC penetration, with higher arrival rate, a sharp decrease of speed is observed when the system becomes saturated (arrival rate ≥ 6000 veh/hr). This is when the demand is higher than the existing capacity, thus, congestions are occurring. As the penetration of the CACC increases, we see an improvement in the speed in all the cases. After running a sequential quadratic programming regression analysis using SPSS, the optimal solution was found and the forecasted model equation generated is:

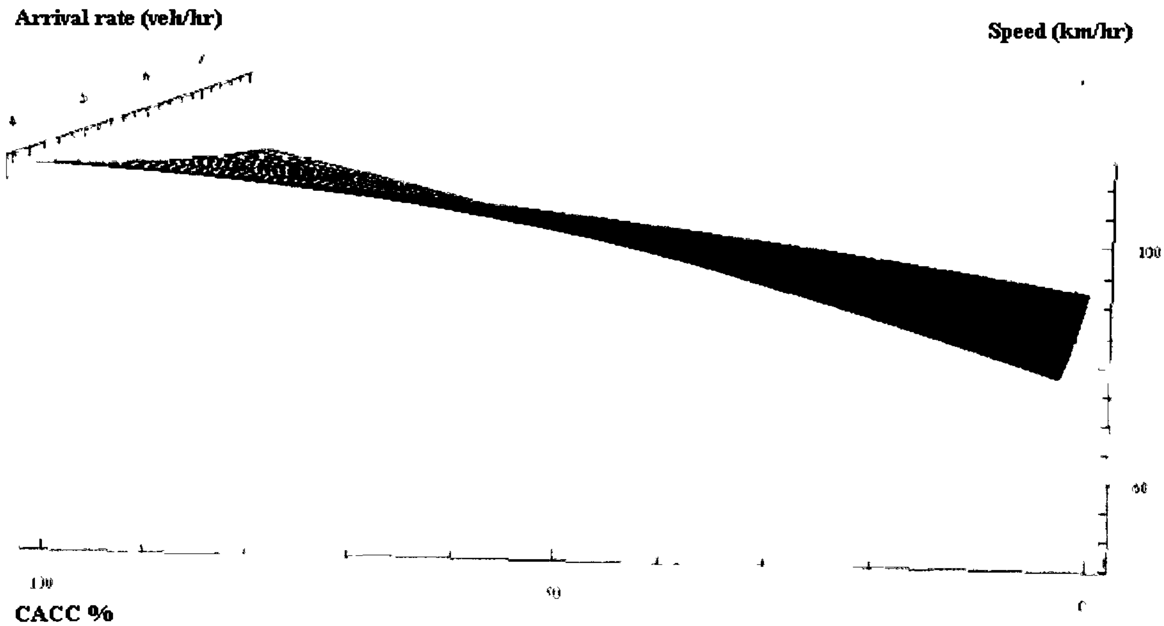
$$\mathbf{Z_2 = 147.19 - 15.1\, \textit{ar} + 0.017\, \textit{pr} + 0.074\, \textit{ar} * \textit{pr} + 0.309\, \textit{ar}\ \hat{}2 - 0.001\, \textit{pr}\ \hat{}2} \qquad (7)$$

Where: ***ar:*** arrival rate of the vehicles
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.

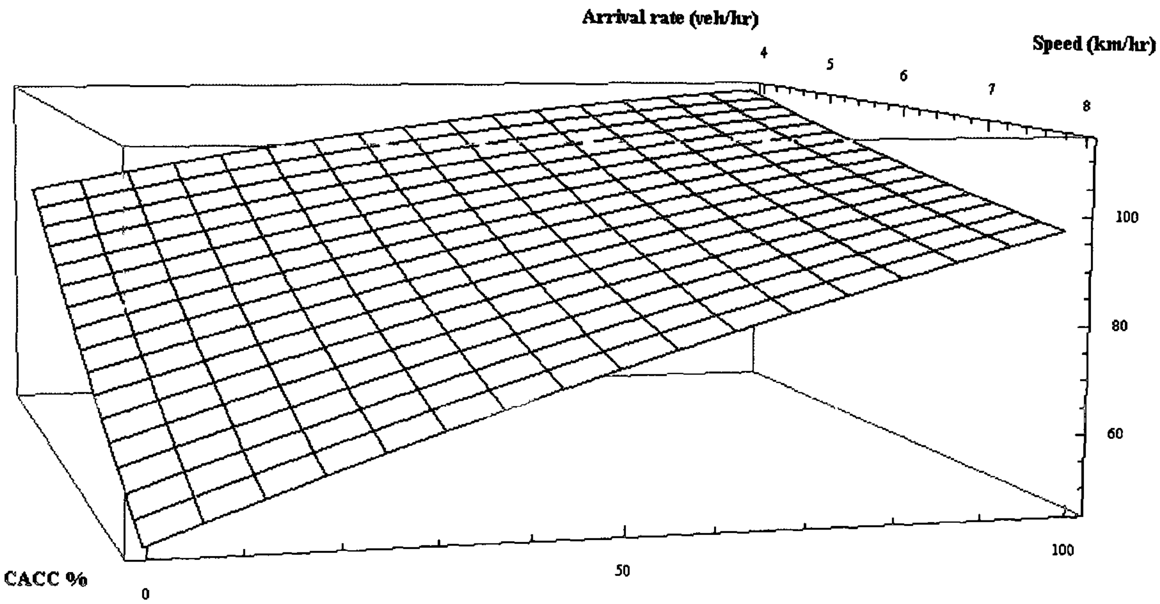


Graph 4. 3D graph of the average speed of the generated model – snapshot 1 (phase 1)



Graph 5. 3D graph of the average speed of the generated model – snapshot 2 (phase 1)

Graph 4 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 graph 5, 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 graph 5 to examine the difference).



Graph 6. 3D graph of the average speed of the generated model – snapshot 3 (phase 1)

It is observed in graph 6 how higher CACC penetration levels at higher arrival rates result in a higher average speed compared to lower CACC penetrations at lower arrival rates, validating the conclusions stated earlier in this section.

4.1.4 Standard Deviation analysis (phase 1)

The standard deviation and variance of the average speed indicate the amount of perturbations and oscillations that occurered in the simulation. The smaller the standard deviation (or speed variance) of the speed, the smoother the traffic flow in the system is. The speed variance has a major effect on the safety and the increasing number of accidents. Accident rates do not necessarily inrease with the increase of the average speed but do increase with the increase in the speed variance (Garber and Gadirau 1988). Figure 17 shows the standard deviation of speed of the vehicles on the 6 km highway in different arrival rates and different CACC penetration levels

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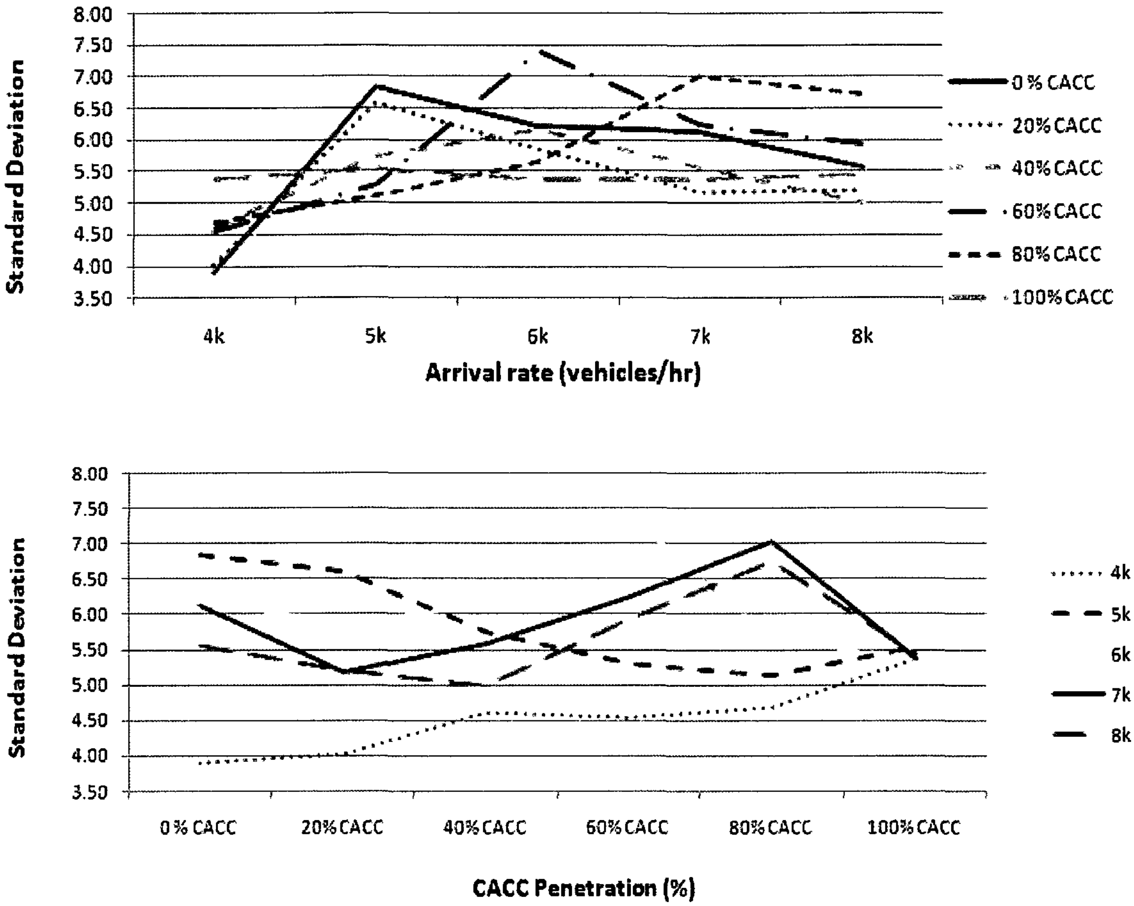

Figure 17. Effect of CACC system on the standard deviation (phase 1)

Conducting ANOVA at this point is necessary to get an accurate conclusion on the significance of the CACC impact, especially due to the complexity of the 2D chart shown in figure 17.

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↓	0.774
0%	40%↓	0.000
0%	60%↓	0.000
0%	80%↓	0.000
0%	100%↓	0.000
20%	40%↓	0.000
40%	60%↑	0.983
60%	80%↓	0.879
80%	100%↓	0.001

Table 14. Standard Deviation: Dunnett T3 Post hoc on 4000 veh/hr (phase 1)

At a low arrival rate of 4000 veh/hr (where there is no traffic congestion), the standard deviation of the 0% CACC was the lowest. That is mainly because most of vehicles were traveling freely without any decelerations. The 0% CACC outperformed the other scenarios in the standard deviation analysis demonstrating that at low arrival rates, the CACC penetration will not affect the speed significantly or reduce the perturbations (that were very minimal in this case). Refer to table 14 for the Dunnett T3 post hoc analysis on the 4000 veh/hr arrival rate. Note that the arrow pointing down in this case indicates that there was a negative change (in the 2nd column) and the standard deviation was higher. An arrow pointing up indicates that there was a positive change (in the 2nd column) and the standard deviation was lower. At the 5000 veh/hr arrival rate, the behavior was different. The 0% CACC had the highest standard deviation and higher CACC penetration lowered the variation of the speed proportionally. In some cases, the increase was not significant but the results of the standard deviation in higher CACC penetration rates were all better than the base case at the 5000 veh/hr, indicating that the CACC effect on the speed is significantly positive in this scenario. The Post hoc tests are shown in table 15.

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.904
0%	40%↑	0.000
0%	60%↑	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↑	0.000
40%	60%↑	0.000
60%	80%↑	0.701
80%	100%↓	0.344

Table 15. Standard Deviation: Dunnett T3 Post hoc on 5000 veh/hr (phase 1)

At higher arrival rates of 6000 veh/hr, the results were harder to analyze. The ramp effect added many perturbations to the system that affected dramatically the accuracy of the standard deviation analysis in phase one. For example, a significant improvement in the standard deviation was observed in most of the CACC penetration levels except in the case of 60% CACC where it was significantly worse than the 0% CACC (refer to table

16). Also, the improvement between the 0% CACC and the 40% CACC was not significant. The same behavior was observed in the cases of 7000 veh/hr and 8000 veh/hr, where no specific pattern for the standard deviation describing the effect of different CACC penetration levels on the traffic average speed of the operating vehicles (refer to tables 17 and 18). In the case of 8000 veh/hr, most of the differences obtained from the conducted One-way ANOVA had no statistical significance.

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.006
0%	40%↑	1.000
0%	60%↓	0.000
0%	80%↑	0.000
0%	100%↑	0.000
20%	40%↓	0.107
40%	60%↓	0.000
60%	80%↑	0.000
80%	100%↑	0.713

Table 16. Standard Deviation: Dunnett T3 Post hoc on 6000 veh/hr (phase 1)

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.000
0%	40%↑	0.000
0%	60%↓	0.987
0%	80%↓	0.000
0%	100%↑	0.000
20%	40%↓	0.004
40%	60%↓	0.000
60%	80%↓	0.000
80%	100%↑	0.000

Table 17. Standard Deviation: Dunnett T3 Post hoc on 7000 veh/hr (phase 1)

Penetration level (i)	Penetration level (j)	Sig.
0%	20%↑	0.972
0%	40%↑	0.713
0%	60%↓	1.000
0%	80%↓	0.110
0%	100%↑	1.000
20%	40%↓	0.975
40%	60%↓	0.049
60%	80%↓	0.053
80%	100%↑	0.001

Table 18. Standard Deviation: Dunnett T3 Post hoc on 8000 veh/hr (phase 1)

The conclusion drawn in this section of analyzing the standard deviation is that it is very hard to analyze the speed variance data due to the excessive perturbations created from the on-ramp which had a negative impact on the accuracy of the standard deviation/variance of the speed. This also shows that in the presence of an on-ramp, all the scenarios in our system had shockwaves that were unpredictable and unrelated to the CACC penetration.

4.2 Phase 2: Special HOV lane with on-ramp

Another version of F.A.S.T. was created with a modified initial configuration. 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 high penetration level of CACC is reached (i.e. market penetration of 60% or more). A small percentage of 10 % manual vehicles were allowed to use the special HOV lanes considering that those vehicles have two or more passengers on board. In addition, CACC equipped vehicles are initially created on the special HOV lane that we will refer to as lane 3. Figure 18 shows the different lanes with their relative numbers. CACC vehicles do not change lanes at any part or time in the system.

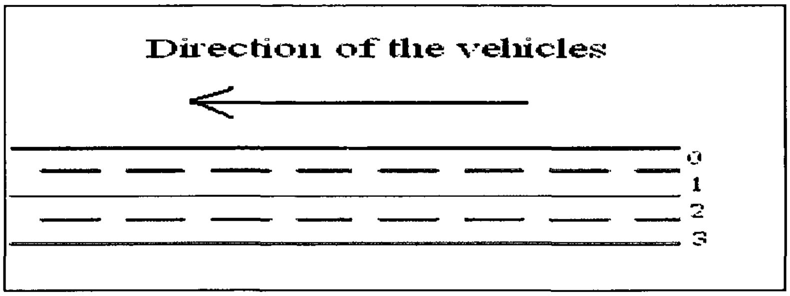

Figure 18. Different lanes in the simulation model by number

Vehicles that are not CACC equipped are uniformly created on the four lanes in the system. However, lane 3 has a much smaller probability than the other lanes to have non CACC vehicles initially created on it 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. Trucks are allowed to operate on HOV lanes following the same rules that impact the non CACC equipped cars. These are the only rules and changes made in the modified version of the simulation model F.A.S.T. A snapshot taken in this phase is shown in figure 19 where the formation of platoon (blue vehicles) on the special HOV lane is observed.

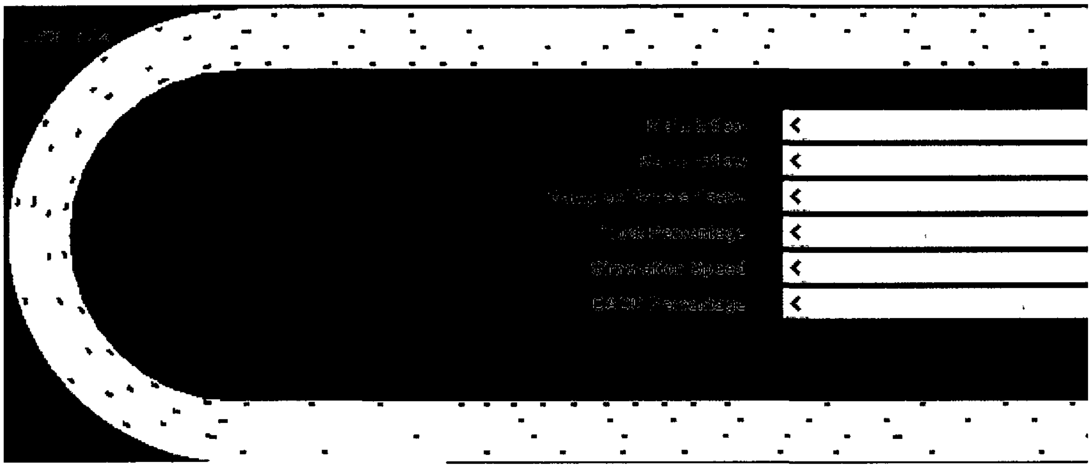

Figure 19. Snapshot of F.A.S.T. in phase 2

A comparison was made between scenarios of low CACC penetration levels of 20% CACC penetration with priority access to the special HOV lanes (referred to as 20% CACC HOV scenario), opposed to scenarios without CACC vehicles operating on the highways (without special lanes). Also, a comparison was made between scenarios of 20% CACC penetration with priority access to special HOV lanes and scenarios with 20% CACC scattered on all the lanes without any special lanes (i.e. the same 20% CACC experiment conducted in phase 1). This scenario is referred to as 20% CACC Scattered. The same initial configuration of F.A.S.T. and the same limitations were used. The experiments included vehicles (cars and trucks) sharing the capacity according to a user pre-defined arrival rate of 4000, 5000, 6000, 7000, and 8000 veh/hr. The vehicles were allowed to overtake and weave. All the experiments had the same previous base assumptions:

- good weather (no rain, snow, fog, etc),
- good pavement conditions,

- no impediments to traffic flow,
- accidents and failures in the operation of the sensors and communication of CACC design equipment were not be taken into consideration.

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 ran for 90 minutes per each replication. A constant arrival rate of 500 veh/hr was set for the vehicles entering the freeway from the on-ramp to create perturbations in the traffic flow.

4.2.1 Flow rate analysis (phase 2)

Figure 20 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.

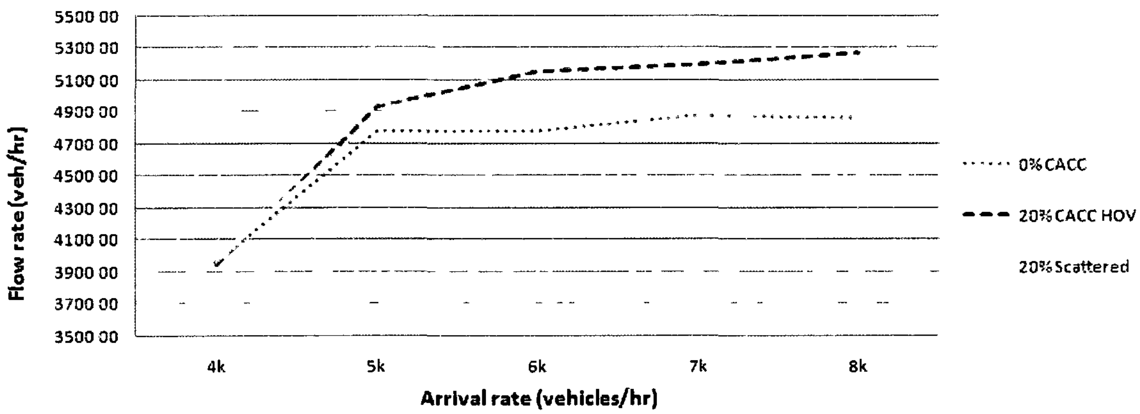

Figure 20. Flow rate analysis (phase 2)

Observing figure 20, 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 were somehow close, ANOVA followed by Dunnett T3 Post hoc tests were conducted to identify the statistical significance in the effect of CACC in the different scenarios studied. For the 4000 veh/hr arrival rate scenario, the ANOVA showed no significance between all the three scenarios. A snapshot taken from SPSS is shown in figure 21.

ANOVA

Flow

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2169.035	2	1084.518	1.372	.259
Within Groups	68764.073	87	790.392		
Total	70933.108	89			

Figure 21. One way ANOVA results for the 4000 veh/hr scenario (snapshot taken from SPSS)

In the 5000 veh/hr scenario, significance was found in both 20% CACC penetration (Scattered and HOV cases) compared to the base case of 0% CACC. However, no significance was found between the two 20% CACC penetration scenarios resulting in a $p > 0.05$. At 6000 veh/hr, a statistical significance between the two 20% CACC penetration scenarios was observed. Table 19 shows the Dunnett T3 Post hoc test conducted in this scenario. A significant improvement was found by using the special HOV lanes for CACC equipped vehicles over the other scenarios.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.001
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 19. Flow rate: Dunnett T3 Post hoc on 6000 veh/hr (phase 2)

In the 7000 veh/hr scenario, no significance was found between the base case of no CACC penetration and the 20% CACC Scattered scenario. However, statistical significance was found between the base case and the 20% CACC HOV. The Dunnett T3 Post hoc test shown in table 20 shows a significant improvement between the 20% CACC HOV case and the base case and also compared to the 20% CACC Scattered scenario.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.760
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 20. Flow rate: Dunnett T3 Post hoc on 7000 veh/hr (phase 2)

In the 8000 veh/hr scenario, the behavior was somewhat similar to the previous case of 7000 veh/hr. No significance was found between the case of no CACC penetration and the 20% CACC Scattered scenario. However, statistical significance was found between the base case of 0% CACC and the 20% CACC HOV scenario. Also, positive statistical significance was found between the 20% CACC HOV scenario and the 20% CACC

Scattered scenario showing the superiority of the 20% CACC HOV scenario over the other scenarios (refer to table 21 for the Post hoc tests).

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.468
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.011

Table 21. Flow rate: Dunnett T3 Post hoc on 8000 veh/hr (phase 2)

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/hr and more) because at free flow conditions, all the scenarios have a free flow traffic able to reach the maximum capacity of the freeway.

4.2.2 Time spent analysis (phase 2)

Additionally, in figure 22, 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.

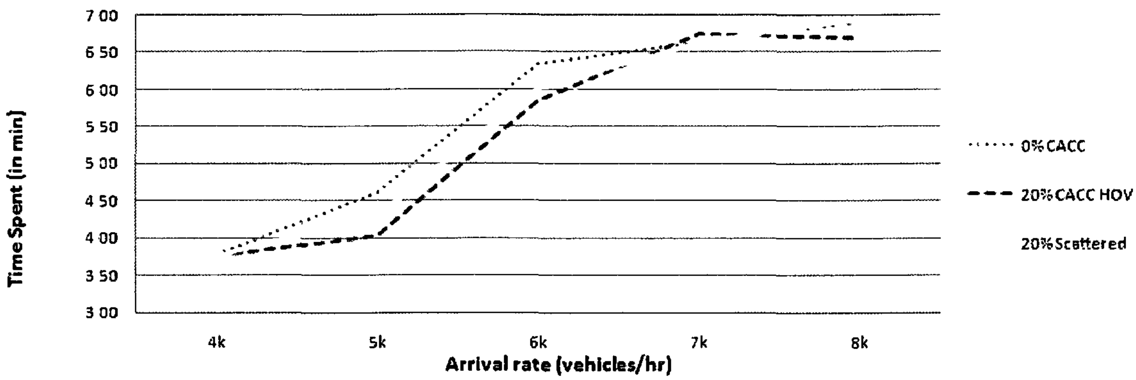

Figure 22. Time spent analysis (phase 2)

An S-shape function was observed with no direct relation between the CACC penetration level and the time spent at 4000 veh/hr arrival rate. ANOVA was conducted resulting in Sig. = .531 (showing that the difference is not statistically significant). At 5000 veh/hr 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 = 0.000 and the difference between the 20% CACC Scattered and the 20% CACC HOV was statistically significant. In the 6000 veh/hr 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/hr and 8000 veh/hr, ANOVA showed no significance in the results (Sig = 0.709 for the 7000 veh/hr and Sig = 0.454 for the 8000 veh/hr). 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 arrival rates (lower than 7000 veh/hr). 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 in the 20% CACC HOV (explained in section 4.2.3), this proves that the density is increasing (from the simple traffic flow formula $q = k * v$, 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.

4.2.3 Average speed analysis (phase 2)

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. Figure 23 shows the average speed at different arrival rates of vehicles. At 4000 veh/hr, the results of ANOVA did not show any statistical significance (p = 0.185) between the means of the three scenarios.

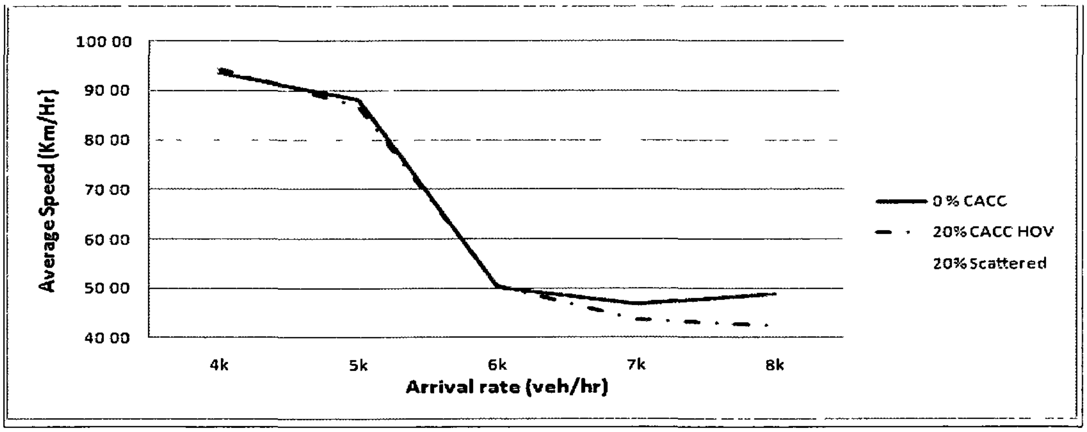

Figure 23 Average speed analysis (phase 2)

At 5000 veh/hr, 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. Table 22 shows the results obtained from the Dunnett T3 Post hoc test.

Penetration level (i)	**Penetration level (j)**	**Sig.**
0%	20% Scattered↑	0.021
0%	20% HOV↓	0.848
20% Scattered	20% HOV↓	0.000

Table 22. Average speed: Dunnett T3 Post hoc on 5000 veh/hr (phase 2)

At 6000 veh/hr, 7000 veh/hr, and 8000 veh/hr, 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. Tables 23, 24, and 25 show the post hoc tests conducted on the scenarios with 6000 veh/hr, 7000 veh/hr, and 8000 veh/hr respectively.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.000
0%	20% HOV↑	0.975
20% Scattered	20% HOV↓	0.000

Table 23. Average speed: Dunnett T3 Post hoc on 6000 veh/hr (phase 2)

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.000
0%	20% HOV↓	0.069
20% Scattered	20% HOV↓	0.000

Table 24 Average speed: Dunnett T3 Post hoc on 7000 veh/hr (phase 2)

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.000
0%	20% HOV↓	0.144
20% Scattered	20% HOV↓	0.000

Table 25. Average speed: Dunnett T3 Post hoc on 8000 veh/hr (phase 2)

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 low average speed in the 20% CACC HOV scenario is that at a higher arrival rates and with sufficient CACC penetration, the speed is being divided among the operating vehicles (CACC and non CACC equipped). This does not necessarily mean 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 on only on one lane – lane 3, out of four available lanes. Thus, the reduction of speed is due to a slower but steady traffic where traffic jams did not occur. This results in higher rate of flow and a lower overall average speed. A study by (Lee, Lee et al. 1998) 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. (Lee, Lee et al. 1998) 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.

4.2.4 Standard Deviation analysis (phase 2)

In phase 2, the analysis of the standard deviation was also not very accurate because of the presence of the on-ramp, unlike the standard deviation analysis in phase 3 where the ramp was not present and the results were clearer and easier to analyze.

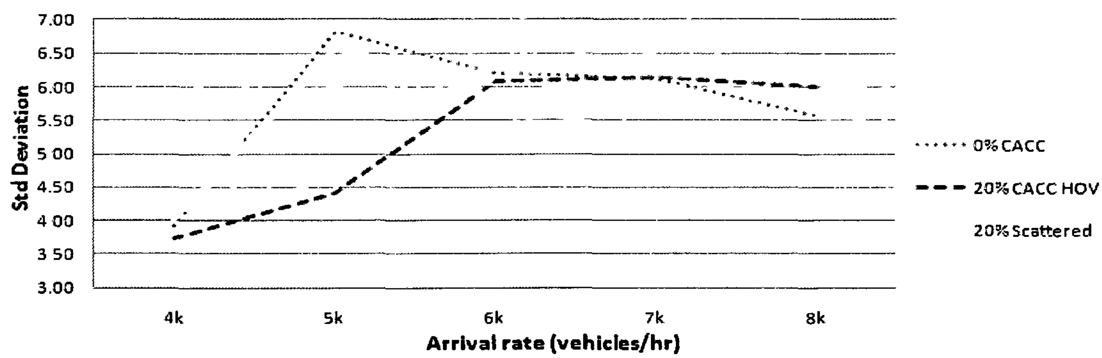

Figure 24 Standard deviation analysis (phase 2)

As shown in figure 24, the results at low arrival rates (4000 veh/hr and 5000 veh/hr) indicated that the 20% CACC HOV scenario improved the quality of the traffic flow by reducing the speed variance and therefore reducing the oscillations resulting from the variation of the speed. ANOVA showed that at 4000 veh/hr arrival rate, there was no statistical significance in the standard deviation difference between the 0% CACC and 20% CACC Scattered scenarios. A significant improvement was observed between the 0% CACC and the 20% CACC HOV, and the 20% CACC HOV and the 20% CACC Scattered (refer to table 26 for the Post hoc results).

Penetration level (i)	**Penetration level (j)**	**Sig.**
0%	20% Scattered↑	0.277
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 26. Standard deviation: Dunnett T3 Post hoc on 4000 veh/hr (phase 2)

At 5000 veh/hr arrival rate, a similar positive behavior (in terms of the 20% CACC HOV scenario) was observed (refer to table 27). The 20% CACC HOV outperformed the other scenarios 0% CACC and 20% CACC Scattered in terms of speed variation reduction by having a smaller standard deviation indicating that placing CACC vehicles at low arrival rates on the special HOV lanes will reduce the variation of the speeds in the system and therefore reduce the amount of shockwaves and speed oscillations.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.395
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 27. Standard deviation: Dunnett T3 Post hoc on 5000 veh/hr (phase 2)

At higher arrival rates, the behavior changed drastically. At 6000 veh/hr, the 20% CACC Scattered outperformed the two other scenarios. As shown in table 28, statistical significance was found between 20% CACC Scattered and the 0% CACC but not between the 0% CACC and the 20% CACC HOV. The Dunnett T3 Post hoc test showed that the results in the 6000 veh/hr arrival rate had only a slight difference where the 20% CACC Scattered outperformed the 20% CACC HOV but with no statistical significance in the difference of the means between the two cases. This difference was exposed even more in higher arrival rates.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.001
0%	20% HOV↑	0.331
20% Scattered	20% HOV↓	0.056

Table 28. Standard deviation: Dunnett T3 Post hoc on 6000 veh/hr (phase 2)

At 7000 veh/hr and 8000 veh/hr arrival rates, the behavior is similar. The 20% CACC Scattered had a lower standard deviation in its replications than the two other scenarios. The results of the Dunnett T3 Post hoc tests are shown in table 29 and 30.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.000
0%	20% HOV↓	0.995
20% Scattered	20% HOV↓	0.000

Table 29. Standard deviation: Dunnett T3 Post hoc on 7000 veh/hr (phase 2)

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.550
0%	20% HOV↓	0.412
20% Scattered	20% HOV↓	0.000

Table 30. Standard deviation: Dunnett T3 Post hoc on 8000 veh/hr (phase 2)

Although the flow rate in the 20% CACC HOV outperformed the other scenarios, at higher arrival rates, the 20% CACC HOV had higher standard deviations of the speed. The reason being is that the on-ramp vehicles are flowing into lane 0 (and vehicles sometimes directly switch to lane 1) inducing perturbations which increases the overall speed variance and the standard deviation of the speed. In addition, the CACC vehicles are limited to lane 3 – the special HOV lane, meaning that the standard deviation is lower on this lane compared to the other lanes. This was validated through extended observations of the traffic flow on lane 3 (where almost no shockwaves were observed). The overall average standard deviation of all the four lanes will eventually be larger because the CACC vehicles are only reducing the standard deviation/variance on one lane (i.e. special HOV lane number 3) and leaving the other three lanes without CACC vehicles that have a significant effect on reducing the variance. This claim is validated in the 20% CACC Scattered scenario, where the CACC vehicles were scattered on all the four lanes resulting in a reduced average standard deviation. However, this does not mean that the 20% CACC Scattered is better because the densities between the scenarios are different. The density in the 20% CACC HOV scenario is higher than the other scenarios, which results in a higher flow but a lower average speed and a higher standard deviation.

Note that due to the nature of this study, the analyses of the average speed and flow rate are more important than the standard deviation analysis.

4.3 Phase 3: Special HOV 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). A snapshot of the model is shown in figure 25.

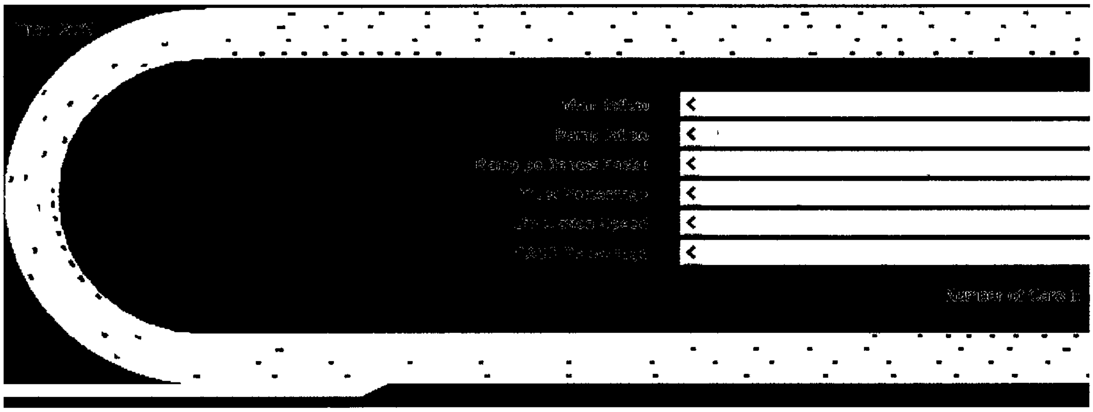

Figure 25. Snapshot of F.A.S.T. in phase 3

4.3.1 Flow rate analysis (phase 3)

Figure 26 shows the rate of flow between the three different cases studied and different arrival rates.

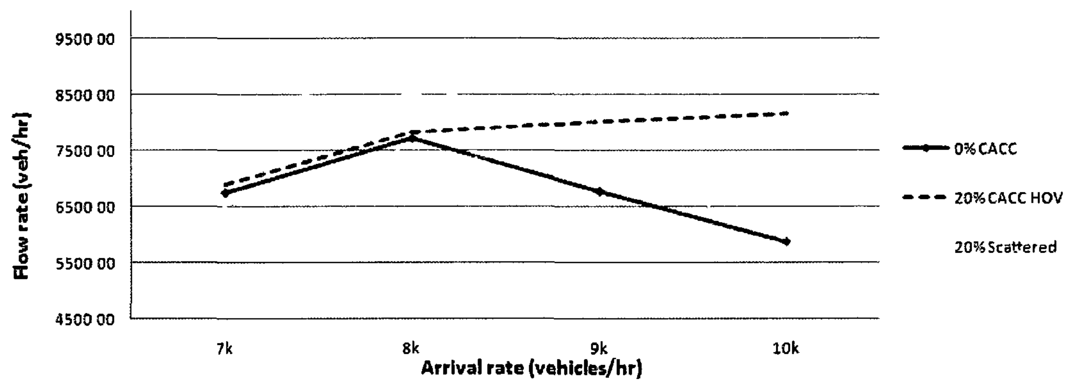

Figure 26. Flow rate analysis of (phase 3)

As observed in figure 26, 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/hr where after that point the flow starts degrading. Note that when validating the model, the arrival rate of 8500 veh/hr 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/hr, the flow rate stayed constant until 9000 veh/hr but then at 10000 veh/hr, it degraded. At 20% CACC HOV, the flow rate kept increasing exponentially beyond the critical point of 8000 veh/hr and even beyond the highest arrival rate of 10000 veh/hr.

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/hr, 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 (refer to table 31).

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↓	0.032
0%	20% HOV↑	0.069
20% Scattered	20% HOV↑	0.000

Table 31. Flow rate: Dunnett T3 Post hoc on 7000 veh/hr (phase 3)

At 8000 veh/hr, a slightly different behavior was observed. There was no statistical significance between the 0% CACC and 20% CACC HOV cases. Significance was also not found between 0% CACC and 20% CACC Scattered. Statistical significance was found between 20% CACC HOV and 20% CACC Scattered (refer to table 32). This shows that in low traffic densities, the effect of CACC is minimal and most of the time not significant. Note that in the previous two scenarios, no congestion was detected.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↓	0.063
0%	20% HOV↑	0.731
20% Scattered	20% HOV↑	0.001

Table 32. Flow rate: Dunnett T3 Post hoc on 8000 veh/hr (phase 3)

At 9000 veh/hr, 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. The results of the Post hoc tests are shown in table 33.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.289
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.023

Table 33. Flow rate: Dunnett T3 Post hoc on 9000 veh/hr (phase 3)

Finally, at 10000 veh/hr 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 (refer to table 34).

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↓	0.963
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 34. Flow rate: Dunnett T3 Post hoc on 10000 veh/hr (phase 3)

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/hr (per four lanes) at the moderate arrival rate scenario of 8000 veh/hr. However, the more we increased the arrival rate above that limit to 9000 veh/hr and 10,000 veh/hr, the queues of the vehicles stretched until reaching the system's entrance and no additional agents we 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/hr and 10,000 veh/hr the system was oversaturated and no agents were entering the system resulting in extenuating a deadlock that was ignored in the analysis.

4.3.2 Time spent analysis

Additionally, in figure 27, 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.

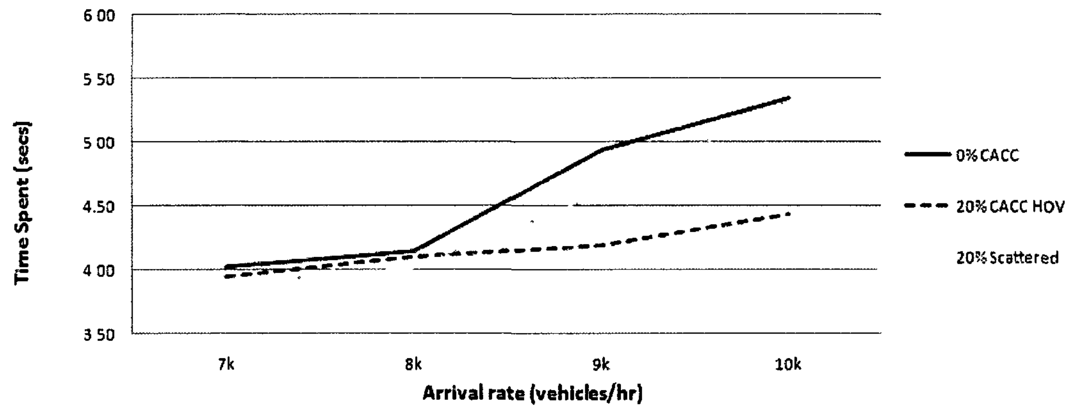

Figure 27. Time spent analysis (phase 3)

The difference in the results is observed at arrival rates higher than 8000 veh/hr where the 0% CACC vehicles took longer to travel through the system while the 20% CACC HOV vehicles evidently performed better than the other two cases. To validate the observations, ANOVA was performed. At 7000 veh/hr, the difference between the 20% CACC HOV and the two other scenarios was not significant. At 8000 veh/hr, ANOVA showed also no statistical significance. At 9000 veh/hr 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 (refer to table 35 for the Post hoc results). The exact same behavior was observed at 10000 veh/hr arrival rate showing the positive impact of CACC in reducing the travel time for the vehicles but only in high arrival rates (refer to table 36 for the Post hoc results).

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.120
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.007

Table 35. Time spent: Dunnett T3 Post hoc on 9000 veh/hr (phase 3)

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.979
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 36. Time spent: Dunnett T3 Post hoc on 10000 veh/hr (phase 3)

4.3.3 Average speed analysis (phase 3)

The average speed was also analyzed. The 20% CACC HOV showed an overall better performance than the other two cases as shown in figure 28.

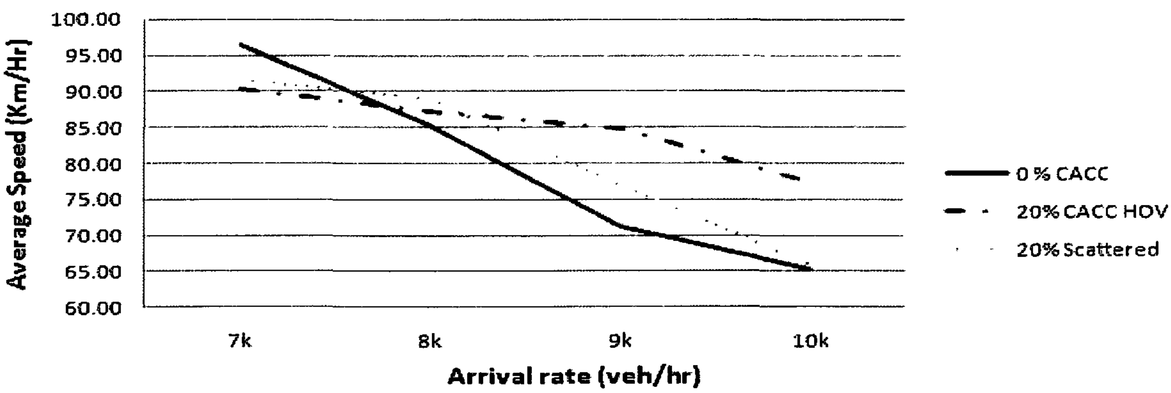

Figure 28. Average speed analysis (phase 3)

ANOVA test was conducted to evaluate the significance of the results and compare the three different cases correctly. In the 7000 veh/hr and 8000 veh/hr (low traffic hours), ANOVA showed no statistical significance between the results of the three cases studied. At 9000 veh/hr, 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 (refer to table 37 for the Post hoc tests). Although the results of the 20% CACC Scattered looked better than the 0% CACC base case, the improvement was not statistically significant.

Penetration level (i)	**Penetration level (j)**	**Sig.**
0%	20% Scattered↑	0.167
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.004

Table 37. Average speed: Dunnett T3 Post hoc on 9000 veh/hr (phase 3)

At 10000 veh/hr, 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 (refer to table 38). The 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 of the average speed. However, the CACC impact is highly dependent on the arrival rates of the vehicles.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.878
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 38. Average speed: Dunnett T3 Post hoc on 10000 veh/hr (phase 3)

It is worth mentioning that in phase 2, 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 (Lee, Lee et al. 1998). In this phase, this effect was not observed because the on-ramp was not present.

4.3.4 Standard deviation analysis (phase 3)

In this phase, the analysis of the standard deviation was clearer and the results were more accurate due to the removal of the on-ramp that created severe perturbations in the results and dramatic variation in the average speed. In figure 29, the improvement in the standard deviation was clearly observed in the 20% CACC HOV scenario compared to the 0% CACC and the 20% CACC Scattered scenarios.

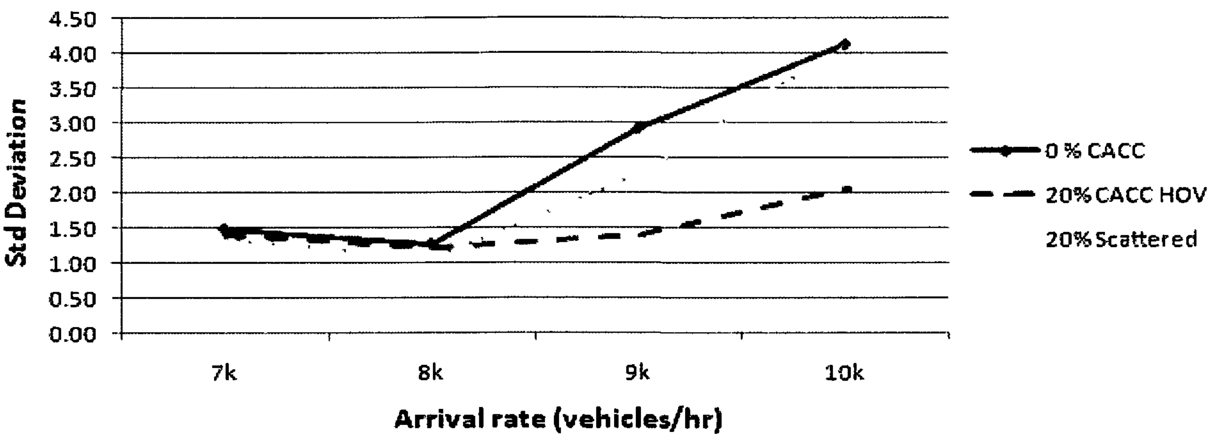

Figure 29. Standard deviation analysis (phase 3)

In order to find out if the differences between the scenarios were statistically significant, ANOVA followed by Dunnett T3 Post hoc tests were conducted. At 7000 veh/hr and 8000 veh/hr arrival rates (which are considered in this case as a low traffic hours scenarios with no congestion occurrences), the ANOVA showed no significance in the results with $p = 0.575$ and $p = 0.342$ for the 7000 veh/hr and 8000 veh/hr arrival rates respectively. At 9000 veh/hr arrival rate, the behavior was significantly different showing the effect of CACC on the speed variance and standard deviation reduction. As shown in table 39, the improvement in the standard deviation was statistically significant between 20% CACC HOV and the two other scenarios, indicating that the placement of the CACC vehicles on special HOV lanes in high traffic hours impacts the traffic speed positively by reducing the variance and the standard deviation (in the case of no ramp presence), and therefore reduce the amount of shockwaves and perturbations in the system. The 20% CACC Scattered scenario had no statistical significance on the standard deviation compared to the 0% CACC scenario.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered↑	0.325
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.021

Table 39. Standard deviation: Dunnett T3 Post hoc on 9000 veh/hr (phase 3)

At 10000 veh/hr arrival rate, the same behavior was observed validating the claim that the CACC vehicles at high traffic arrival rate must be placed on special HOV lanes in order to reduce the shockwaves in the system. The 20% CACC HOV scenario showed a statistical significance in the improvement of the standard deviation compared to the two other scenarios. The difference between the 20% CACC Scattered and the 0% CACC had no statistical significance and the results were almost similar. The Dunnett T3 Post hoc results are shown in table 40.

Penetration level (i)	Penetration level (j)	Sig.
0%	20% Scattered	1.000
0%	20% HOV↑	0.000
20% Scattered	20% HOV↑	0.000

Table 40. Standard deviation: Dunnett T3 Post hoc on 10000 veh/hr (phase 3)

CHAPTER 5

CONCLUSION

In this dissertation, a microscopic traffic simulator, F.A.S.T. that simulates the effect of Cooperative Adaptive Cruise Control (CACC) equipped vehicles on a four-lane freeway was proposed. The simulations were based on different arrival rates of traffic and different penetration rates of CACC equipped vehicles and in different configurations. CACC vehicles are not available in the car market at this point. It is assumed that their spreading will grow in the future. Thus, the contribution of this research was to explore the impact of this new technology on the traffic dynamics by means of microscopic traffic simulation, and to project any potential problems that it might have. Furthermore, 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.

This dissertation has described new algorithms for controlling CACC vehicles efficiently and increasing their positive effect of the traffic flow rate and performance. A progressive deployment strategy was developed to maximize the traffic flow at low CACC penetration levels by restricting the operation of CACC vehicles on HOV lanes referred to as *Special HOV lanes*.

The methods put forth here show encouraging results under challenging conditions and the CACC positive impact was shown to be competent. The analysis involved one-way ANOVA tests, Dunnett T3 post hoc analysis, 2D/3D analysis regression analyses with Sequential Quadratic Programming.

This chapter re-examines the results in light of the original thesis and the hypotheses that were stated in Chapter 3. In addition, the strengths and weaknesses of the study are stated. Finally, the chapter concludes with an exploration of the future directions of the research.

5.1 Hypotheses and claims revisited

A number of significant contributions can be drawn from this research. In the first part of the study, the first claim (or hypothesis) was addressed using various experiments on a highway simulation model with four lanes and an on-ramp (for more details refer to chapter 4).

Claim #1. There is a significant difference in traffic performance metrics using CACC vehicles on freeways with different penetration levels compared to not using CACC vehicles.

This claim was validated in section 4.1 in chapter 4 by modeling the behavior of traffic under different CACC penetration levels. From the analysis conducted, it was shown that the effect of CACC is minimal in low traffic density highways. Also, the effect of CACC is proportional to the level of CACC penetration - meaning that the highest positive effect will be at high traffic arrival rate and high CACC penetration level. The findings of this phase of the study validated previous studies like (Arnaout and Bowling 2010), (VanderWerf, Shladover et al. 2003), and (Arem, Driel et al. 2006). Also, the experiments showed that the average time spent in the system by the operating vehicles when embedding CACC vehicles was less than the time spent in other scenarios but was very sensitive to the CACC market penetration as well as the arrival rate of the vehicles. The average speed analysis of scenarios with high CACC penetration and high traffic density also outperformed the other scenarios. The standard deviation analysis showed that in high arrival rates and critical traffic density, shockwaves will always occur and are unpredictable even in higher CACC penetration level (in the case of a ramp or a presence of any other perturbation generator).

An alternate approach used to study the effects of CACC on traffic performance was by running experiments in a low CACC penetration level. This approach was used as a second phase taking into account that the CACC penetration level is not going to be high in the near future, so a progressive transition strategy was introduced by giving the CACC equipped vehicles priority access on HOV lanes (or special HOV lanes). This brings us to the second claim of this research:

Claim #2. There is a significant difference in traffic performance metrics using CACC vehicles, given priority access to special HOV lanes, at low penetration levels compared to not using CACC vehicles.

This claim was validated in section 4.2 and 4.3 of chapter 4. By restricting the operation of CACC equipped vehicles on special HOV lanes allowing the transition of only 10% of manual (non CACC) vehicles on these lanes, experiments and analyses were conducted to identify the feasibility of this approach. Three scenarios were compared: (1) 0% CACC, (2) 20% CACC scattered on all the lanes meaning without the presence of special HOV lanes, and (3) 20% CACC placed solely on special HOV lanes. The third scenario outperformed the two other scenarios in the rate of flow of the traffic, especially at high traffic arrival rates. An interesting finding was observed when comparing the average speed of the three scenarios. As it looked that the 20% CACC HOV scenario performed poorly (lowest average speed among the three), the results were perfectly logical. By having a reduced average speed and an increased flow of traffic, the speed was divided among all the operating vehicles and therefore the flow became steady (i.e. the number of congestions decreased) but at a lower average speed. This resulted in a lower average speed compared to the two other scenarios studied. Also, the standard deviation of the speed tended to be higher in the 20% CACC HOV scenario. Only one lane was getting the benefit of the perturbations-reduction (due to the CACC presence) while the other three lanes had no CACC presence and had higher amount of perturbations. This claim was verified by extended observations of the simulations in the 20% CACC HOV cases. By scattering the CACC vehicles on all the lanes resulted in a lower standard deviation but also a lower flow of traffic. The reason of the reduced standard deviation of the speed in the 20% CACC Scattered is because the density was smaller (explained by the lower flow of traffic and a higher speed). In other words, with a smaller density, fewer cars were in the system at one point and this does not mean that the quality of traffic in the 20% CACC Scattered scenario outperformed the 20% CACC HOV scenario, especially that this study is mainly focused on the flow as the primary performance metric. Therefore, the study recommends placing the CACC vehicles on special HOV lanes opposed to scattering them on all the lanes. At higher CACC market penetrations (≥ 40% CACC), the study recommends scattering the CACC vehicles on all the lanes because at such penetration, the results of phase one have proved the significant impact of the CACC technology if the vehicles were scattered on all the lanes.

A variation in the configuration of the two previous phases was created to confirm our previous results. As the on-ramp induced major variations in the speed and reduced the flow of traffic significantly, the same experiments were conducted without an on-ramp. The results proved that the placement of the 20% CACC vehicles on special HOV lanes is significantly better than scattering the 20% CACC on all the lanes. Therefore, in low CACC penetration levels (≈ 20% CACC), it is more efficient to place the CACC vehicles together to get the most out of the CACC technology. In addition, the average time spent by the vehicles in the 20% CACC on special HOV scenario was significantly less than the other scenarios proving the superiority of the proposed progressive deployment strategy. The average speed of the 20% CACC HOV scenario, although exponentially decreasing, was higher (higher average speed) and smoother (lower standard deviation in the speed) than the other scenarios. The reason being is the absence of the on-ramp that creates oscillations and shockwaves and reduces the average speed.

5.2 Strengths of the CACC technology

The nature of CACC systems makes it particularly applicable in critical scenarios with high traffic density where the efficiency lies in reducing traffic congestions, smoothening the flow, and therefore improving the traffic performance. The superiority of the CACC system in its effect on the traffic performance was demonstrated in this dissertation compared to scenarios without CACC. Other than improving the flow of traffic, the

CACC reduces that speed variance (without the presence of a ramp) which has a major impact on reducing accidents and increasing the safety in the driving process.

As the experiments conducted proved the competence of such systems and their relative strengths, other observations must also be considered. The robust nature of the proposed ECACC algorithm allowed CACC vehicles to operate on the modeled highway smoothly in a steady flow, and at very close distances. Without interfering with the operation of the other non CACC equipped vehicles, placing the CACC vehicles on special HOV lanes gathered the equipped vehicles together without having to be concerned with non CACC vehicles interfering in the CACC platoons (refer to figure 4.15 for the observation of this behavior). The non equipped vehicles do not break the platoons once they are already created. The reason being is that non CACC vehicles operate on the traffic models IDM (for acceleration and deceleration) and MOBIL (for lane changes) and the latter has the incentive criterion that will not be met if a non CACC vehicle wanted to break into a certain platoon. More clearly, the CACC vehicles are too close together to allow a non CACC equipped vehicle to transition itself in between those vehicles and still meet the incentive criterion (due to a higher time gap > 0.5 seconds). Therefore, the non CACC vehicles end up changing lanes (if within the HOV percentage – having two passengers or more) to a position before or after the platoon, and not in the middle of it. This observation is very realistic in real life as drivers would not feel comfortable squeezing their vehicle between two cars where the separating distance is very small. Finally, installing the CACC system to a vehicle is fairly simple, especially that most of the newer vehicle models already have the ACC system installed. A vehicle can be equipped with the CACC system by simply adding a DSRC, a frontal radar, and the appropriate software without having to be concerned with dealing with RSUs or TSOs.

5.3 Weaknesses of the CACC technology

For the effect of CACC systems to be maximal on the traffic performance with a presence of a perturbation generator (such as a ramp), the traffic has to be at high density (saturated) before any significant impact of CACC is observed. This is not considered as a weakness of the CACC system because at low traffic hours, no congestions are witnessed and since no major degradation in the performance caused by the CACC system is observed, the CACC system could be simply turned off at these low arrival rates (or even better it could be used for safety and comfort which is of course recommended). In scenarios with high arrival rates but low CACC penetration levels, the research showed the necessity of having special HOV lanes for the CACC vehicles to operate on without changing lanes. As this approach results in an improved flow of traffic and less congestions, the practicality of this approach was not fully considered. Most of the vehicles operating on the highway will want to exit the highway at some point of their travel. This will result in platoons breaking apart and decelerations induced from the lane changes (especially if the exit is located on the far right or lane 0 while the special HOV lane is located on the far left or lane 3). Thus, a major weakness in the CACC systems (in this study) is that when vehicles are very close to each other, when one of the vehicles would want to break away from the platoon it will create perturbations to the platoon while splitting from it, before the vehicles in the platoon connect to each other again. The same problem would be faced if a platoon was too large and a manual vehicle was trying to join the special HOV lane. Another issue that might arise from the CACC system (that was studied by (Steven E. Shladover 2009)) is the public accessibility for such a technology. With such a small 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 major challenge facing the success of the CACC technology.

5.4 Future work

Perhaps the most important improvement needed in the proposed model F.A.S.T. is to be extended to allow accidents to occur and 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. Other future directions in this research involve optimizing the performance of the proposed ECACC algorithm to cope dynamically with the traffic arrival rates and density.

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All further information (including the traffic model and its documentation) can be found under: http://www.georgearnaout.com.