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to the

CENTER FOR MULTIMODAL SOLUTIONS FOR CONGESTION MITIGATION (CMS)

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ABSTRACT

Advanced driver assistance technologies are continuously being developed to enhance traffic safety. Evaluations of such technologies typically focus on safety and there has been limited research on the impacts of such technologies on traffic operations. Given the difficulty in observing such impacts in the real world, traffic simulation is used in this project to replicate such technologies under various demand and market penetration scenarios. The project focuses on Advanced Cruise Control (ACC) and Lane Change Assist (LCA). These two systems were replicated in a microsimulator (CORSIM) and their impacts were reported separately and in combination along a test network.

It was concluded that the ACC can significantly increase speeds for congested conditions, even at the lowest market penetration scenario tested (20% ACC in the traffic stream). However, when ACC is present, bottlenecks can be created at locations where a significant number of drivers are likely to turn their ACC off. When only the LCA was present the number of lane change maneuvers increased, the throughput (VMT) increased, and travel time was not significantly affected. When both LCA and ACC were present, conditions improved significantly, and similarly to when ACC was available by itself.

EXECUTIVE SUMMARY

There is a wealth of advanced vehicle technologies available on the market and under development by major automobile manufacturers that are expected to change vehicle interactions within the traffic stream, particularly with respect to car-following, lane changing, and gap acceptance characteristics. All these systems still need to be evaluated, since their impacts on traffic conditions are not entirely known. In addition, if such systems become prevalent in the traffic stream, their effects need to be well known so that they can be incorporated into traffic analysis tools.

Microsimulation has been used extensively in evaluating traffic flow, considering vehicle capabilities (acceleration, deceleration, speed) as well as driver behavior. These tools replicate individual vehicle movement according to pre-determined car-following, lane changing, and other algorithms, to evaluate traffic conditions on the highway network. Thus they can be very useful in evaluating the impact of advanced driver assistance technologies in a network. The CORSIM (Corridor Simulation) microsimulator was developed originally by the Federal Highway Administration (FHWA) and has been used extensively around the world. FHWA has provided the code to the University of Florida's McTrans Center, essentially assigning intellectually property rights and control of future development of CORSIM to McTrans. With access to its source code, algorithms can be modified to be able to replicate and evaluate selected advanced vehicle technologies that may impact traffic flow.

The main objective of this research is to modify and use CORSIM to evaluate traffic operational impacts of selected advanced vehicle technologies. The evaluation considers different demand and market penetration scenarios and evaluates traffic operational impacts both at the point and traffic network levels. The two technologies selected are Adaptive Cruise Control (ACC) and Lane Change Assist (LCA). The ACC use either a radar or laser setup to allow the vehicle to decelerate when approaching another vehicle and accelerate again to the preset speed when traffic allows. The driver is able to choose the desired maximum speed and the time headway to be developed automatically by the vehicle. The LCA warns drivers of traffic presence at the target lane, indicated by the driver through the turn signals, before or while changing lanes.

Following a thorough literature review, the researchers developed recommended modifications to specific microsimulator components and simulated driver actions. These modifications consider specific algorithm changes as well as input and output information. Based on these first two tasks, the CORSIM micro-simulator was modified to be able to model the selected vehicle technologies. A test network was developed in CORSIM to evaluate the changes under different demand and market penetration scenarios. For each vehicle technology implemented, CORSIM was tested to evaluate the reasonableness of the results, and the sensitivity of the output as a function of various input parameters. The last task tested the list of scenarios developed and assessed the relative impacts of specific advanced vehicle technologies on congestion using the modified CORSIM.

The following are concluded from the research:

- The ACC resulted in slightly increased speeds for the lower demand scenarios, and in significant speed increases for congested conditions. Improvements are observed and congestion is eliminated even for the lowest market penetration scenario tested (20% ACC). Generally, the concept of constant time headways appears to be promising for reducing congestion.
- When ACC is present, bottlenecks can be created at locations where a significant number of drivers are likely to turn their ACC off. When such systems are implemented in the future, extra care should be taken in advance to address potential issues generated by these locations.
- The ACC resulted in a decrease in throughput for nearly all scenarios tested because the ACC produced on the average longer time headways. However, the time headway distribution under ACC was a user-defined input and a different distribution might result in slightly different throughputs;
- When only the LCA was present the number of lane change maneuvers increased, the throughput (VMT) increased, and travel time was not significantly affected. When both LCA and ACC were present, conditions improved significantly, and similarly to when ACC was available by itself.

Generally, the research conducted here was useful as an initial evaluation, but it was based on some key assumptions which would need to be further explored. First, there was no consideration for drivers turning on and off their systems throughout the test network, and it was assumed that drivers with the technology would use it the entire time. Second, the desired time headway distribution selected by drivers in the field is not known. A similar point can be made regarding the LCA: it is not known yet how drivers would use such systems in everyday traffic, and thus the assumptions used in the simulator would need to be revisited once field data are available.

CHAPTER 1 INTRODUCTION

PROBLEM STATEMENT

There is a wealth of advanced vehicle technologies available on the market and under development by major automobile manufacturers that are expected to change vehicle interactions within the traffic stream, particularly with respect to car-following, lane changing, and gap acceptance characteristics. For example, some autonomous systems such as Adaptive Cruise Control (ACC), which automatically controls speed and headway with the front vehicle, and Lane-Change Assist (LCA), which provides warning messages during lane change maneuvers, are already available on the market and have been partially tested to evaluate their traffic impacts. Cooperative systems, which rely on communication between vehicles and infrastructure, are still under development, but are already being tested. All these systems still need to be evaluated, since their impacts on traffic conditions are not entirely known, especially at the network level. In addition, if such systems become prevalent in the traffic stream, their effects need to be well known so that they can be incorporated into existing traffic analysis tools.

One such tool, microsimulation, has been used extensively in evaluating traffic flow, considering vehicle capabilities (acceleration, deceleration, speed) as well as driver behavior. Existing microsimulators however, have been developed based on the traditional vehicle performance, and do not yet have the capability to evaluate traffic stream conditions considering the advanced vehicle technologies currently available or being developed. The CORSIM

(Corridor Simulation) microsimulator was developed originally by the Federal Highway Administration (FHWA) and has been used extensively around the world. FHWA has provided the code to the University of Florida's McTrans Center, essentially assigning intellectually property rights and control of future development of CORSIM to McTrans. CORSIM replicates individual vehicle movement according to pre-determined car-following, lane changing, and other algorithms, to evaluate traffic conditions on the highway network. With access to its source code, these algorithms can be modified to be able to replicate selected advanced vehicle technologies that may impact traffic flow. Such modifications would allow for testing and evaluation of various advanced technologies with respect to their impact on traffic flow and congestion.

Given the need to evaluate new advanced vehicle technologies, and the capability of CORSIM to replicate vehicle movement at the individual vehicle level, the main objective of this research is to modify and use CORSIM to evaluate traffic operational impacts of selected advanced vehicle technologies. The evaluation considers different demand and market penetration scenarios and evaluates traffic operational impacts both at the point and traffic network levels.

METHODOLOGY OVERVIEW

The first task consists of an extensive literature and industry review to identify specific vehicle technologies that are being considered or are under development, which may affect the traffic operational quality and capacity of the highway system. The potential impacts of each identified vehicle technology were assessed for specific aspects of traffic flow modeling. Each vehicle-related technology identified was examined and evaluated to assess its impact on various routine driver actions.

Following the literature review, the researchers developed recommended modifications to specific microsimulator components and simulated driver actions. These modifications consider specific algorithm changes as well as input and output information.

Based on these first two tasks, the CORSIM micro-simulator was modified to be able to model the selected vehicle technologies. A test network was developed in CORSIM to evaluate the changes under different demand and market penetration scenarios. For each vehicle technology implemented, CORSIM was tested to evaluate the reasonableness of the results, and the sensitivity of the output as a function of various input parameters.

The last task tested the list of scenarios developed and assessed the relative impacts of specific advanced vehicle technologies on congestion using the modified CORSIM.

REPORT ORGANIZATION

The second chapter of this report provides a summary of the literature review with respect to advanced vehicle technologies, while the third chapter describes the two technologies selected for testing and their implementation into CORSIM. The fourth chapter provides detailed information on the analysis process, including a description of the test network and the testing procedures and scenarios. The data analysis results are provided in the fifth chapter, while the last chapter summarizes the conclusions from this research and recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

There are a significant number of vehicle technologies being developed by major automobile manufacturers that could affect the flow of traffic, particularly with respect to car-following, lane changing and gap acceptance characteristics. These technologies can be grouped into two major types: Assisted Driving Systems and Connected Vehicle by USDOT/RITA (consisting of vehicle-to-vehicle and vehicle-to-infrastructure communications). The first part of this chapter provides an overview of each of those systems and discusses their potential impact on traffic flow and congestion. The second part provides an overview of past research related to the evaluation of these systems, while the third part discusses the replication of such technologies using modeling and simulation. The last part provides a summary of the literature review findings and recommendations on the technologies to be evaluated in this project.

OVERVIEW OF VEHICLE TECHNOLOGIES

Assisted Driving Systems

Driver assistance systems are based on the idea that an on-board computer can help drivers make driving more convenient and safe by recognizing potentially dangerous situations. They are based on sensors and cameras connected to a central vehicle information system that provides warnings to the driver or directly intervenes in the driving process by braking or accelerating. These types of systems can be classified as: Side assist, Front assist, Brake assist, Blind corner monitor and Parking and rear assist. Each of these systems is described in the following paragraphs.

Side Assist

Such systems are related to actions that the driver would take related to lateral movement. There are two types of side assist functions, and a different type of technology is applied to each of those two functions.

Lane Keeping: For this system a camera built into the vehicle (roughly above the inside rear view mirror) detects lane markings to the left and to the right of the vehicle, through an image processing lane tracking algorithm. Using this information it evaluates the position of the vehicle.

This technology can provide two types of assistance: a) the system warns the driver when the vehicle begins to move out of its lane (unless a turn signal is on in that direction) on freeways and arterial roads (l*ane departure warning)*, and b) the system makes an active intervention to help the driver stay in the lane (*lane keep assist).*

These two systems use the same base technology, but in the first case, the vehicle does not make an active intervention; the system just warns the driver to make the correction. Figure 2-1 illustrates the difference between these two systems.

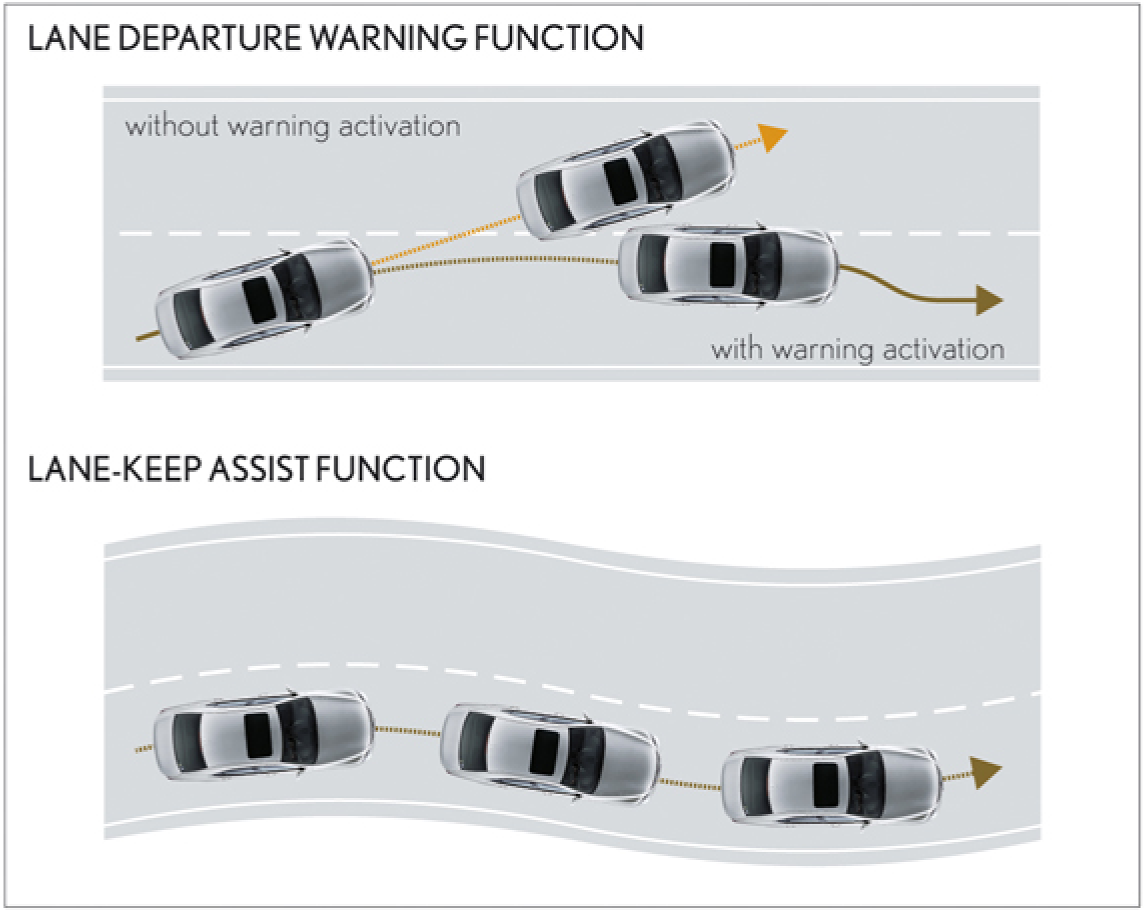

Figure 2-1. Difference between Lane Departure Warning and Lane Keep Assist (Source: http://www.toyota-global.com/innovation/safety_technology_quality/ safety_technology/technology_file/active/lka.html)

For the *Lane keep assist,* if the car tends to drift off the lane, the control unit analyzes the degree of deviation, transmits corrective steering pulses to the electrical mechanical power steering and the steering reacts with an active intervention. If the driver takes his or her hands completely off the steering wheel, the system makes a sound and displays a message making a so-called takeover request. If the driver does not put his or her hands on the wheel for a longer period of time, the function automatically turns itself off. If required, the system can be counteracted by the driver by softly steering against it. The driving assistant does not react if the vehicle moves out of its lane after the driver has indicated a lane change by turning on the turn signal. If the maximum action available is not enough to stay in lane or the speed falls below 60 km/h, the feature warns the driver with a vibration of the steering wheel. Then it is up to the driver to take corrective action.

Figure 2-2 depicts the operation of the *lane keep assist* system. As soon as the driver turns the system on, a yellow control symbol appears in the panel indicating that the system is activated and is evaluating the position of the vehicle. When the system identifies the road markings the symbol turns green and the system is ready to take action in the case of lane departure.

Figure 2-2. Lane Keep Assist System Operation
(Source: http://www.volkswagen.com/vwcms/master_public/ virtualmaster/en2/experience/innovation/assistance_systems/lane_assist.html)

Lane Changing: The system warns drivers of traffic presence in the target lane. The target lane is indicated by the driver through the turn signals, before or while changing lanes. This feature employs short-range radar sensors located in the front and rear bumpers that monitor the zone to the side and rear of the car on both the left and the right side. If another vehicle is driving alongside in the blind spot area or closer than 50 meters, the system will display a red warning symbol in the associated side mirror. If the driver ignores the warning and signals a lane change, the red warning symbol will start to flash and emit a warning sound inside the car. This system operates from speeds above 60 kilometers per hour and is therefore not used in heavy inner-city traffic, since the system would be providing too frequent a warning.

The side assist features discussed above are available in all S and CL Class vehicles of Mercedes Benz, Nissan Infiniti, Luxury Phaeton and Passat CC (VW), most Audi models, Lexus, BMW, Volvo, GM (Cadillac and Buick) and Toyota.

With respect to traffic flow, the side assist has a potential impact on lane changing characteristics and particularly gap acceptance for lane changing.

Front Assist

In these systems, a device is placed at the front of the vehicle so that it can monitor the traffic ahead, detect any vehicle (in the same lane) and calculate the distance and the speed relative to it. These functions are associated with the Adaptive Cruise Control (ACC) technology.

ACC systems use either a radar or laser setup to allow the vehicle to decelerate when approaching another vehicle and accelerate again to the preset speed when traffic allows. Laser-based systems are significantly lower in cost than radar-based systems; however, laser-based ACC systems do not detect and track vehicles well in adverse weather conditions nor do they track extremely dirty (non-reflective) vehicles very well. While laser-based sensors must be exposed, radar-based sensors can be hidden behind plastic fascias.

Using the signals from the radar sensor, the control unit computes not just the distance to the vehicle ahead but also the car's speed relative to it. If there are several vehicles within the sensor's field of coverage at the same time, the system selects which of the vehicles it should track. The radar sensor is not capable of detecting stationary obstructions, such as the end of a tailback or crash barriers. If approaching a slower vehicle ahead or another vehicle cuts in front, the automatic distance control slows down the car by initiating corrective controls in the engine management and, if necessary, in the braking system too. If the required rate of deceleration exceeds 30 percent of the vehicle's maximum stopping power, the driver will be prompted by visual and audible warning signals to apply the brakes manually.

In Fancher et al. (1998), UMTRI and USDOT published the results from a Field Operational Test regarding ACC. Their objectives were primarily focused on human interaction with the system, and the central finding was that ACC is remarkably attractive to most drivers. In 2006, Toyota developed Radar Cruise Control with All-Speed Tracking Function. This version of the system maintains continuous cruise control, from 0 km/h to the highest speed, and the manufacturer claims it can handle repeated starts and stops which are common when driving on congested highways. This feature is available on high-end vehicles from almost every vehicle manufacturer in the United States.

This technology has a potentially significant impact on car following and lane changing characteristics, since it provides distance headway control and brake assist functions.

Brake Assist (Pre-Crash System)

This system is designed to reduce the damage caused by a collision, by maximizing the driver braking performance. Based on the increased speed with which the brake pedal is actuated, the system recognizes that the driver wishes to perform an emergency stop. For as long as the driver operates the brake pedal, the brake assist system increases braking pressure hydraulically via the ABS/ESP unit, up to the control range of the anti-lock brake system. When the brake pressure applied by the driver decreases, the system reduces brake pressure again to the actual level indicated by the driver. Thanks to its intelligent control strategy, the active system is hardly noticed by the driver. Pre-crash systems are available on many high-end vehicles.

This system has a potential impact on car following characteristics; however its impact would be more significant in crash avoidance rather than operational performance while driving.

Blind-Corner Monitor

This technology is related to visual functions in approaching crossings and has a potential impact on gap acceptance characteristics. The system uses a camera and a color display screen to minimize the danger of collisions when approaching crossings, or 'T' junctions. A camera with a built-in prism is installed in the middle of the front grille of the vehicle, and it sends a picture to the display screen positioned inside the car. When the car approaches a crossing where visibility is reduced to the left and/or to the right, the image on the display shows a view of approximately

20 meters in both directions, at an angle of 25°. This helps the driver see approaching vehicles, bicycles and pedestrians that would otherwise not be visible. Figure 2-3 illustrates such a situation and both the driver's view and monitor screen.

This type of technology has a potential to affect safety rather than operational conditions in the field.

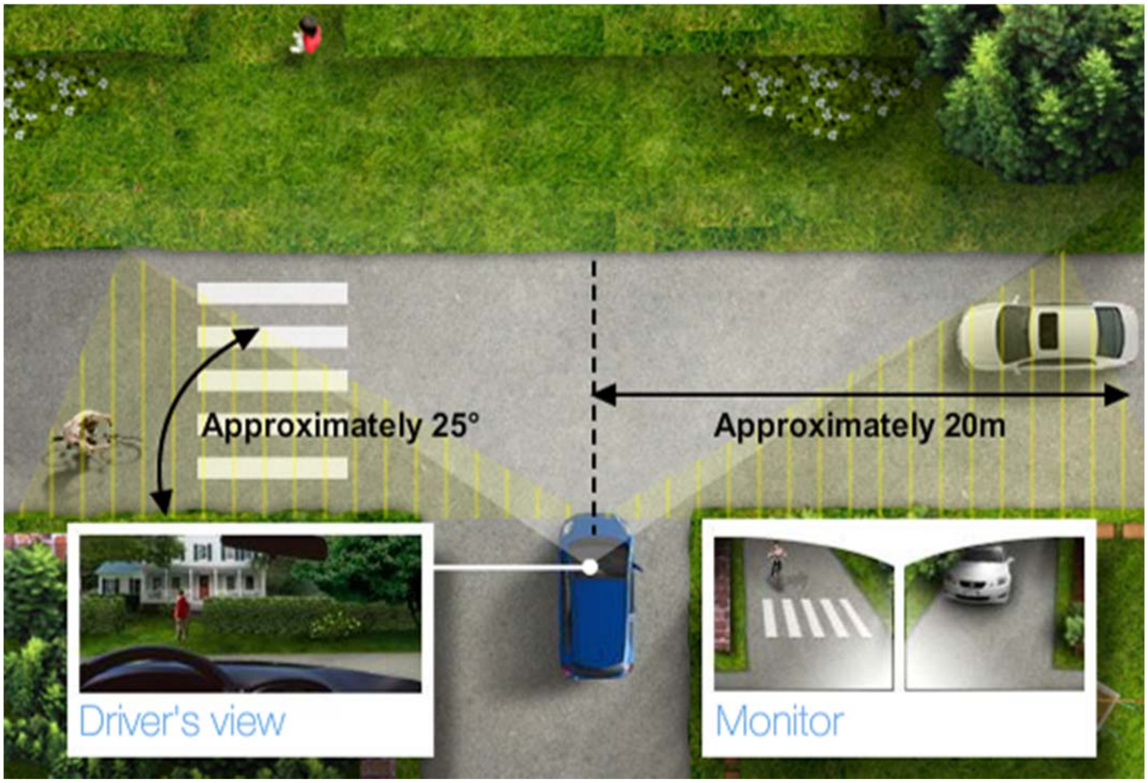

Figure 2-3. Blind Corner Monitor
(Source: http://www.toyota-global.com/innovation/safety_technology_quality/safety_technology/technology_file/active/multi_angle.html)

Rear and Park Assist

These systems are related to parking maneuver functions and consist of rear assist (for rear maneuvers) and park assist systems (for every type of maneuver during parking).

Rear Assist: It enables the driver to spot any obstacles behind the vehicle quickly and easily, courtesy of the camera built into the vehicle tail. It is activated as soon as the driver engages reverse gear. Colored lines on the display indicate whether the way is clear: green lines show the area behind the vehicle, yellow lines the path corresponding to the angle the steering wheel is turned to. The driver has to simply align the red line with the curb he/she wishes to stop in front of. Figure 2-4 provides an image of the monitor in operation.

Figure 2-4. Rear Assist with Colored Lines on the Display
(Source:http://www.volkswagen.com/vwcms/master_public/virtualmaster/en2/experience/innovation/assistance_systems/rear_assist.html)

Park Assist: The most important elements of this technology are ultrasonic sensors, with up to six of these located in the rear and/or front bumpers. The sensors monitor a range of up to 150 centimeters behind and in front of the vehicle. The system is activated when reverse gear is engaged or below a speed of 15 km/h.

The system uses the principle of the echo sounder. The control unit periodically triggers the sensors which emit an ultrasonic signal with a frequency of 40 kHz (kilohertz). The control unit then switches the sensors to reception, so that they can pick up the sound waves reflected off an object. Based on the passage time of the ultrasonic waves (the time that elapses between emitting the signal and receiving the reflection), the system calculates how far the sensor is from the obstacle. The control unit calculates the distance between the vehicle and the obstacle based on the information from at least two sensors using the triangulation method.

An enhancement of this technology consists of systems that automatically guide the vehicle into the gap for parking in one move. The ultrasonic sensors determine whether the parking space in question is a suitable one. They compare the area available with the length of the vehicle. From an optimum starting position, all the driver has to do is press the accelerator and the brake to park the vehicle.

This technology has a probable impact on the time the driver takes to park the vehicle, but it is not expected to significantly impact traffic flow.

Connected Vehicle by USDOT/RITA

In the U.S., the Connected Vehicle Research by USDOT/RITA (http://www.its.dot.gov/connected_vehicle/connected_vehicle.htm)—formerly known as Vehicle Infrastructure Integration (VII) and IntelliDrive^{SM}, envisions that every car manufactured in the U.S. would be equipped with a communications device and a GPS unit so that data could be exchanged between vehicles (vehicle-to-vehicle communication – V2V) and with a nationwide, instrumented road system (vehicle-to-infrastructure communication). These types of technologies are being developed by a Coalition that supports the Connected Vehicle Research. This coalition consists of the U.S. Department of Transportation, state and local governments, their representative associations and light vehicle manufacturers (BMW, Chrysler, Daimler Benz, Ford, General Motors, Honda, Hyundai, Nissan, Subaru, Suzuki, Toyota and Volkswagen).

This initiative involves a series of technologies directly linking road vehicles to their physical surroundings. The goal is to provide a communications link between vehicles on the road, and between vehicles and the roadside infrastructure in order to increase the safety, efficiency, and convenience of the transportation system. In the future, automakers hope to offer this technology in all cars at which point communication between vehicles will be possible through a dedicated short range communication (DSRC). However, the systems cannot detect vehicles that are not equipped with similar technology.

A brief description of the two major components of the Connected Vehicle Research is given below:

V2V

Today, vehicles can be equipped with multiple safety sensors, including a long range scanning sensor for adaptive cruise control, forward vision sensors for object detection, mid-range blind spot detection sensors and long-range lane change assist sensors. V2V has the ability to replace all of these sensors with one advisory sensor that will provide all-around, instantaneous traffic intelligence. This promises a better and significantly less-costly way of sensing other vehicles in the vicinity while driving.

Using V2V communication, a vehicle can detect the position and movement of other vehicles up to a quarter of a mile away. If vehicles are equipped with a simple antenna, a computer chip and GPS (Global Positioning System) technology, each vehicle will know where the other vehicles are, whether in blind spots, stopped ahead on the highway but hidden from view, around a blind corner or blocked by other vehicles. The information received from the devices can be transmitted to the driver through visual, audible and tangible warnings (such as seat vibrations).

Vehicle-to-Infrastructure

One major project of this initiative is the Cooperative Intersection Collision Avoidance System (CICAS). This government-industry initiative in the United States intends to develop and deploy a cooperative vehicle-infrastructure system to improve intersection safety. There are three operational concepts for CICAS being researched:

• CICAS-Violation (CICAS-V): a system that warns the driver via an in-vehicle device when it appears likely that the driver will violate a traffic signal or stop sign;

• CICAS-Stop Sign Assist (CICAS-SSA): a system that uses a Dynamic Message Sign to inform drivers on the minor road when it is unsafe to enter the intersection due to insufficient gaps in traffic on the main road;

• CICAS-Signalized Left Turn Assist (CICAS-SLTA): a system that uses a Dynamic Message Sign or an in-vehicle sign to tell drivers when it is unsafe to make an unprotected left turn at a signalized intersection.

The CICAS-V system is being developed by the VSC 2 Consortium, and the primary objective is to develop an effective prototype that is suitable for deployment. The basic CICAS-V concept is that both the vehicle and the intersection would be equipped with DSRC radios.

Another approach is the vehicle to hand-held devices (V2D), that intend to warn cyclists and pedestrians through messages sent to cell phones and devices on the bike, avoiding potential collision.

The Connected Vehicle Research seems to be a technology with significant potential for affecting car-following, lane changing and gap acceptance characteristics. Since those systems have not yet been implemented, information with respect to their quantitative impacts is not available.

FIELD TESTING AND EVALUATION OF ADVANCED VEHICLE ASSISTANCE TECHNOLOGIES

A limited amount of testing has been conducted to evaluate advanced vehicle assistance technologies. Most recently, an UMTRI (University of Michigan Transportation Research Institute)-led team in close collaboration with the U.S. DOT and its partners, developed a set of verification tests, which served to demonstrate the effectiveness, repeatability and general readiness of IVBSS (Integrated Vehicle-Based Safety Systems) for field operational testing, were conducted on test tracks and on-road, and all tests resulted in passing grades for the technologies tested.

The track tests were used to verify that the prototype integrated system meets design requirements and to evaluate system performance. The tests were of four types:

- Rear-end Crash Threat Tests: this test evaluated the appropriateness of a forward crash warning when a vehicle approaches, from behind, another vehicle in many situations of speed and position of both vehicles;
- Lane-Change Crash Threat Tests: this test intends to verify the appropriateness of a warning when a vehicle is trying to change lanes in different situations, for example, when the blind zone is occupied by a vehicle and when there is an approaching vehicle.
- Road Departure Crash Threat Tests: this test intends to verify the appropriateness of a lateral drift warning when the vehicle drifts toward an opposing-traffic lane, toward a clear shoulder and toward an adjacent jersey barrier and a curve speed warning when the vehicle encounters a small radius curve.

- Multiple-Threat Tests: this test intends to verify the appropriateness of the three warnings combined.

These tests showed that the assisted driving systems available on the market work properly and have a potential impact on car following and lane changing characteristics.

In Fancher et al. (1998), a field operational test was conducted to observe human interaction with the Adaptive Cruise Control (ACC). Volunteers drove as their personal car, a vehicle equipped with this system. For a period of two weeks, 84 participants drove the vehicle, while 24 drivers were given the vehicle for five weeks. The subjects could choose whether to use or not the conventional cruise control during the first week, and the ACC during the subsequent weeks.

The results obtained from instrumented measurements on-board the vehicles, and from questionnaires answered by drivers, show that participants were remarkably attracted to ACC. The majority of drivers were comfortable with the system because of its relief of driving stress, associated with the inefficient motions of the throttle pedal applied during manual driving. Regarding utilization of ACC, drivers seemed to make individualized choices about when to use the system since utilization rates for drivers ranged from less than 20% to almost 100% under comparable conditions. Also, results show a higher rate of ACC usage on surface streets, where traffic conflict and complexity for driving tasks are present. Lastly, it was concluded that ACC usage cultivated a less aggressive driving style in many participants.

A Field Operational Test was conducted by Viti et al. (2008) in the Netherlands, assessing impacts of Adaptive Cruise Control and Lane Departure Warning on road capacity, safety and emissions. Their main conclusion revolves around the fact that drivers overrule ACC systems and rely on their own driving skills even without being in emergency situations. However, it is possible that this driving behavior could change with time (the more drivers use the systems, the more they would rely on them) or as a result of modified algorithms that better suits driver's expectation.

In addition to these operational field tests, recent research by Golias et al. (2002) summarized the traffic efficiency expected by each of the available driver assistance systems. Table 2-1, edited from Golias et al. (2002), summarizes their findings. The authors concluded that platooning (i.e., a series of vehicles in communication with each other), adaptive cruise control and lane change and merge collision avoidance are the only vehicle support systems that have a potential to impact traffic efficiency.

Table 2-1. Assessment of Traffic Efficiency of Advanced Driver Assistance Systems

		Traffic efficiency	
VEHICLE		Speed adjustment	Headway adjustment
general vehicle control	automatic stop and go	L	L
	Platooning	H	H
	speed control	L	L
	adaptive cruise control	H	H
collision avoidance	road and lane departure collision avoidance	L	L
	lane change and merge collision avoidance	L	H
	rear end collision avoidance	L	L
	obstacle and pedestrian detection	L	L
	intersection collision avoidance	L	L
vehicle monitoring	Tachograph	L	L
	alerting systems	L	L
	vehicle diagnostics	L	L

H: high, important impact; L: low, limited or insignificant impact

MODELING VEHICLE TECHNOLOGIES AND THEIR TRAFFIC IMPACTS

Current traffic simulators are based on algorithms that were not designed to address the most recently developed driver assistance technologies. In order to analyze the traffic impacts of these systems, changes and additions to existing models have to be implemented to incorporate the elements of driver behavior and systems design that could affect traffic flow dynamics. This section discusses the development and implementation of such changes, as well as the results obtained by these efforts regarding traffic impacts of specific vehicle technologies.

Van Arem et al. (1997) developed the MIXIC 1.3, which is a microscopic traffic simulation model, was designed by TNO and the Transport Research Centre (AVV) of the Dutch Ministry of Transport, Public Works and Water Management, to assess the impacts of advanced vehicle technologies in traffic. It was used to study the impacts of ACC on consecutive motorway stretches, and it contains detailed submodels describing drivers, vehicles, assisting systems and their interfaces.

Within the microscopic model, new positions and states are calculated in each time step by a driver and vehicle model. The combined driver/vehicle model produces the longitudinal new vehicle acceleration, and a decision to change lanes or not. During each iteration, the driver model produces the driver actions, consisting of the lane change action and the new pedal and gear positions. Next, the vehicle model calculates the resulting acceleration of the vehicle.

The driver model consists of three main components. The first two describe the actual driving behavior: these are the lane-change model and the longitudinal driver model. In each simulation time step, these sub-models are executed to decide whether or not a driver changes lanes and the driver's actions on the vehicle controls. For vehicles that are equipped with ACC, the third component models the interaction between the driver and the ACC; this part indicates when the ACC is switched on and off.

The longitudinal driver model of the MIXIC distinguishes free-driving and car-following behavior. During each iteration, a desired acceleration is calculated for both situations and the most restrictive one is used. In the free-driving situation, the driver only attempts to reach or maintain a desired speed within certain boundaries. This desired speed, which is assumed to be constant for each driver, indicates the speed that would be maintained in the absence of other traffic.

In the car-following situation, the driver adjusts the vehicle speed and/or following distance with respect to traffic ahead, based on the assumption that the driver tries to keep the relative speed to the lead vehicle and simultaneously attempts to keep the distance headway at a desired value. When a vehicle is equipped with an ACC system, then this system will take over parts over the longitudinal control task. The driver has the liberty to switch the ACC on or off. The authors assumed that drivers have the ACC switched on as much as possible. However, since the system has a limited deceleration range, the driver must overrule it in situations where hard braking is required. Therefore, a model was developed to describe the interaction of a driver with the ACC system.

The vehicle model describes the dynamic behavior as a result of the interaction with the driver and the road, taking into account the ambient conditions. The input variables from the driver model are the position of the accelerator pedal and the force applied on the brake pedal and for vehicles with a manual gear shift also the gear and clutch position. In summary the authors concluded that, especially at high flow levels, the parameters of the intended headway function have a strong effect on the simulation results.

In a more recent paper, Van Arem et al. (2006) analyzed the impact of Cooperative Adaptive Cruise Control (CACC) on traffic-flow characteristics using the MIXIC model. CACC is a further development of ACC that adds vehicle-to-vehicle communications, providing the system with more and better information about the vehicle it is following, making the ACC controller able to better anticipate problems, enabling it to be safer and more natural in response. In order to simulate a CACC system in MIXIC, a CACC model had to be designed in the microsimulator. Since the basis of the longitudinal driver model is the calculation of a driver's desired acceleration, if a CACC takes over part of this driving task, a reference acceleration of the CACC controller is calculated instead. The computation of the reference acceleration, based on the distance and speed difference between the two vehicles, is complicated, and depends also on the communication between vehicles. The testing with MIXIC showed that enhancement of highway capacity due to CACC is restricted to specific situations and that degradation of performance could also occur because of this system. The authors indicated there is a need to test this and similar systems in realistic congestion simulation scenarios to fully understand their impacts on traffic.

VanderWerf et al. (2001) developed a set of mathematical models to predict the effects of driver assistance systems such as ACC on traffic flow dynamics and capacity. The mathematical models developed and validated include vehicle-following logic, merging of vehicles entering a highway, free driving logic and vehicle dynamic response to speed change commands. This model was tested in a subsequent paper, where Vander Werf et al.(2002) showed the effects of varying the proportion of ACC systems on lane capacity using the previously developed models. Using Monte Carlo simulation, the authors concluded that autonomous ACC systems are unlikely to significantly affect traffic dynamics. Simulations using the cooperative ACC (using vehicle-to-vehicle communications to enable closer vehicle following) with priority access to designated lanes, exhibited a potential increase in highway capacity. The authors concluded that the cooperative ACC could lead towards highway automation, potentially doubling capacity of a highway lane at a high-market penetration.

Bareket et al. (2003) reports a methodology to assess ACC behavior, by modeling and simulating measured ACC performance. The analyses indicated that vehicles with ACC exhibits significant overshoots in speed and range clearance in response to the preceding vehicle's changes in speed. The authors also emphasize that this type of research can contribute to the development of ACC systems that could improve traffic flow in specific conditions of high traffic density.

Brackstone et al. (2009) analyzed different aspects of the ACC: social, legal, network efficiency, environment, and human factors issues. The conclusions show a potential for ACC to improve road capacity, although the system was not designed for that. The authors indicate that 20% of market penetration seems to be the minimum required to start noticing changes in traffic. The main benefit of the system appears to be the significant reductions in acceleration variation during car-following situations, reducing driver's stress, fuel consumption and harmful emissions. The safety aspects were considered as well, and it was concluded that there are still liability issues regarding time headways below the nationally recommended.

LITERATURE REVIEW SUMMARY AND CONCLUSIONS

In summary, advanced driver assistance systems have significant potential to improve safety and roadway capacity. Several of these systems are already available, particularly in high-end vehicles, by several manufacturers. The two technologies that seem to have the greatest potential to affect traffic operations in the near term are the ACC and the Lane Change Assist (LCA). Although platooning will likely have an impact on both speed and headways, the coordination of vehicle maneuvering depends on vehicle-to-vehicle communication capabilities. The details regarding the manner in which such coordination would operate in the field are not presently known, and thus evaluation of this technology will not be considered in this research.

Although studies related to ACC show potentially positive effects on traffic, the majority of the field experiments conducted are linked to safety issues. In modeling the potential traffic impacts of the ACC, the results are mixed: some authors (for example, VanderWerf et al., 2002) conclude that ACC are unlikely to significantly affect traffic dynamics, while others (for example, Brackstone et al. (2009) incidate there is a potential for ACC to improve roadway capacity once market penetration exceeds 20%). One important variable that seems to affect the results is the desired headway selection. Another one is the utilization of such systems by drivers. LCA systems have not yet been evaluated quantitatively with respect to their potential traffic impacts.

Based on the literature review, the two systems evaluated in this project are the ACC and LCA, since they are the ones with the most potential for improving traffic operations, and the literature review revealed that their impacts have not been conclusively documented.

CHAPTER 3 DESCRIPTION OF THE TECHNOLOGIES EVALUATED AND THEIR IMPLEMENTATION INTO CORSIM

Even though the technologies selected to be evaluated in this project are already available on the market, the specifics of each algorithm are not available by each manufacturer. The algorithms used here were developed and tested by academic institutions. The first section of this chapter summarizes the specifications of the two systems tested (ACC and LCA), while the second section explains how the two systems were replicated in CORSIM. For comparison purposes, the algorithms currently used in CORSIM to replicate the movement of vehicles without these advanced technologies is presented in Appendix A.

ALGORITHMS IMPLEMENTED IN THE SIMULATOR

This section describes the algorithms used to modify the existing car-following, gap acceptance and lane-change models in the traffic simulator. These algorithms have been adapted from ones previously reported in the literature.

Adaptive Cruise Control

The ACC algorithm used in this project is based on Fancher et al. (1998), employing an approach that uses speed to control time headway. The main conceptual features of this algorithm are that it maintains the maximum speed selected by the driver if there is no impeding traffic, it adjusts the speed to maintain the desired time headway with the vehicle ahead, and it autonomously switches back and forth between these two operational modes.

Figure 3-1 illustrates this concept.

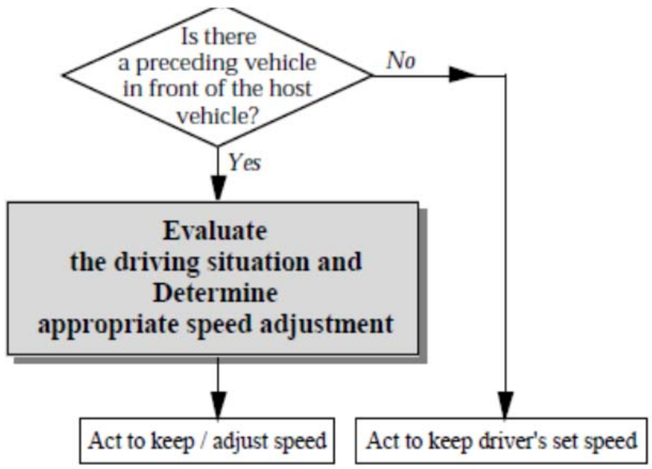

Figure 3-1. Employing Speed to Control Headway. (Source: Fancher et al., 1998)

This algorithm is based on the following functions and operations:

- Driver's actions override the system's actions
- The system will never achieve a speed higher than that selected by the driver
- If the driver brakes, the system disengages and does not automatically reengage thereafter
- If the driver accelerates, the system automatically reengages thereafter with the previous set up parameters
- Preceding vehicles at 525 ft or less are the only ones considered
- The system only works at speeds higher than 20 miles/hour

The first step of the algorithm is to search for the first vehicle in front of the subject vehicle and in the same lane and compute the distance between them. Following that, the algorithm is divided into a simple case (when there is no slower traffic ahead -beyond 525 ft), and an advanced case (when the headway is adjusted as a function of the lead vehicle speed.

For the simple case, the system adjusts the subject's speed to achieve and maintain the maximum speed set up by the driver (Vmax). The acceleration (a) is computed every time step to adjust the control, and is calculated according to Mezny et al. (2009):

$$a = \frac{Vmax - V}{T} \tag{3-1}$$

Where:

- a is the acceleration of the subject vehicle,
- Vmax is the maximum speed set up by the driver,
- V is the current speed of the subject vehicle,
- T is a calibrated parameter to control the reaction time of the algorithm. This parameter allows for a smooth transition of speeds during ACC control, and it is not related to the driver's reaction time. Using a value close to a driver's reaction time could result in extremely high acceleration values when the difference between Vmax and V is very high. Therefore, this parameter can be interpreted as the reaction time of the system.

The advanced case is based on the desired time headway selected by the driver (T_h in seconds), which is a control-system parameter. The desired gap distance (R_h in feet) is a linear function of lead vehicle speed (V_l):

$$R_h = V_1 \text{ x } T_h \tag{3-2}$$

Figure 3-2 illustrates these parameters. R_h is the desired gap distance (from the ACC vehicle to the lead vehicle) towards which the controller attempts to converge.

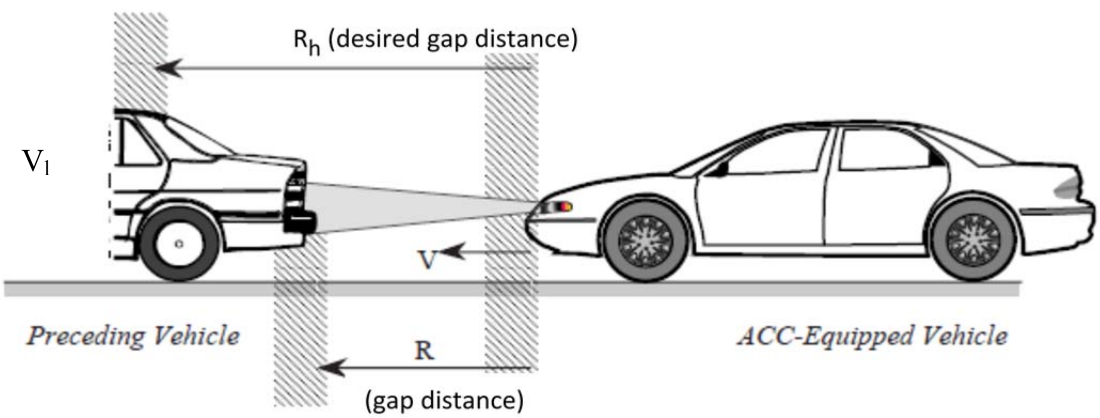

Figure 3-2. Parameters for Headway Control (Modified from Fancher et al., 1998)

The parameter R_h is used by the algorithm to compute the speed command (V_c), which is the desired speed for the ACC vehicle to achieve the desired gap (R_h) in a smooth manner:

$$V_c = V_1 + \frac{R - R_h}{T_0} \tag{3-3}$$

Where:

- V_c is the speed command,
- V_l is the speed of the leading vehicle,
- R is the current gap distance,
- R_h is the desired gap,
- T_0 determines the closing rate and the value suggested by Fancher et al. (1998) is 11 sec.

The desired acceleration is calculated according to equation (3-1), substituting Vmax for V_c. According to Mezny et al. (2009), to limit the number of repetitions and avoid the algorithm reacting to minor changes, the acceleration is updated only if either of these conditions is met:

- R differs from R_h by more than 1 percent (if R equals 199 ft and R_h is 200 ft, the difference is 0.5% and the condition is not met),
- V_l differs from V_c by more than 5 percent (if V_l equals 100 ft/sec and V_c is 98 ft/sec, the difference is 2% and the condition is not met),
- The difference between V_l and V_c is greater than the difference between V_c and V (if V_l (100 ft/sec) minus V_c (98 ft/sec), that is 2 ft/sec, then V needs to be at least 96.9 ft/sec for this condition to be met).

Lane Change Assist (LCA)

The LCA algorithm implemented is based on LeBlanc et al. (2008). The algorithm uses a simplified rationale, adjusted to the simulator characteristics. It provides a warning sound when the subject vehicle is changing lanes and has the turn signal on, and at least one vehicle is within the unsafe zone (

Figure 3-3). The warning sound beeps continuously when the turn signal is on until there is no vehicle inside the zone. If the subject vehicle attempts a lane change maneuver without turning on the signal indicating the target lane, the system is not triggered; therefore there is no warning sound.

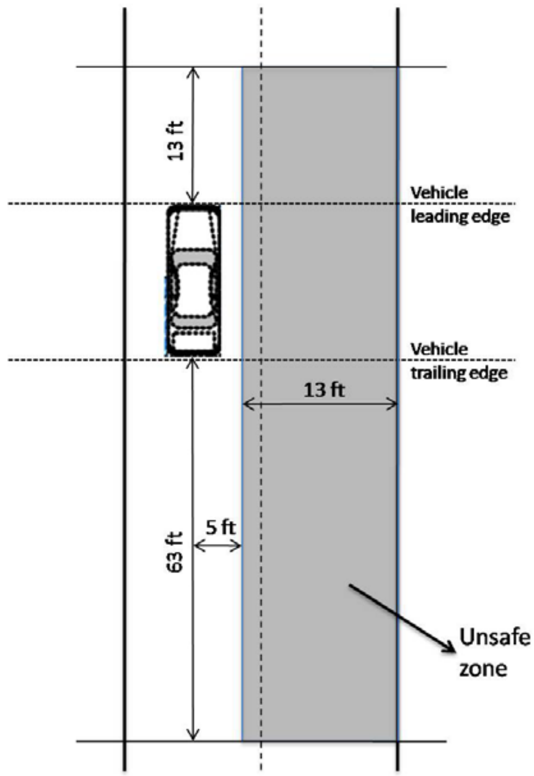

Figure 3-3. Unsafe Zone for LCA with Both Sides Symmetric (Modified from LeBlanc et al., 2008)

IMPLEMENTATION OF THE TECHNOLOGIES

This section describes how the two algorithms described above were adapted so that they can be implemented in CORSIM.

Car-following for ACC

In order to replicate the ACC in CORSIM, a combination of the Intelligent-Driver Model (IDM) (M. Treiber and D. Helbing 2001) along with the algorithm presented in the previous section (Fancher et al., 1998) was used. The IDM algorithm had to be used since the algorithm presented above is not a car-following model; it simply replicates how the technology works inside a vehicle. Kesting et al. (2008) used this algorithm to model ACC-based car-following, because the input parameters of an ACC system (vehicle's speed, distance to vehicle ahead and speed difference) are the same as many time-continuous car-following models.

Since the ACC reaction time (of the order of 0.1 and 0.2 seconds) is negligible compared to the human reaction, ACC systems specify the instantaneous acceleration as a function of the speed, net distance and approaching rate to the leading vehicle. In order to simulate ACC systems appropriately, car-following models must meet the following criteria: they must be collision-free; the dynamics should correspond to natural driving, providing adaptations to new traffic situations to be performed without any oscillations; and they must support the selection of desired speed and desired time gap, which are preset by the driver. These criteria are met by the IDM.

Although the IDM is a car-following model that presents a crash-free collective dynamics and an intelligent braking strategy that provides a smooth transition between acceleration and deceleration, it was developed for single-lane roadways. However, the IDM responds to the cut-in maneuvers with strong braking which is not possible with an ACC system (Kesting et al. 2010), providing inconsistent results.

After further testing to refine the results, the car-following model implemented to replicate ACC used the acceleration term adapted from (Fancher et al. 1998) and (Mezny et al. 2009) and the desired minimum gap from the IDM, as follows:

$$\dot{v} = \frac{v^* - v}{5}, \qquad (3\text{-}4)$$

Where:

- $\dot{v}$ - acceleration;
- v - actual speed;
- v^* is given by:
    - $v^* = v_l + \frac{s - s^*}{11}$ - if the current gap to the leading vehicle (s) is less than 525 ft or (3-5)
    - $v^* = v_{max}$ - if the current gap to the leading vehicle (s) is more than 525 ft, (3-6)

    where:

    - v_l – speed of the leading vehicle;

- v_{max} – desired maximum speed (preset by the driver);
- s – current gap to the leading vehicle
- s* - effective desired minimum gap, defined as: $s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}}$ (3-7)

  where:

  - s_0 – minimum distance in congested traffic (2m);
  - T – desired time gap (preset by driver);
  - Δv – speed difference between the lead and follower vehicle;
  - a – maximum acceleration;
  - b – comfortable deceleration.

The parameters T and v_0 are implemented in the simulator as distributions that can be input by the analyst, and the market penetration level of ACC is also a variable. The other variables follow CORSIM defaults; the CORSIM acceleration and deceleration functions were not modified.

Lane- Changing for LCA

As discussed previously, the LCA operates as a warning in potentially dangerous situations to drivers that express the desire (through use of their turn signal) to change lanes. Although the system does not directly affect the operation of the vehicle, it may lead to changes in the driving behavior. As concluded in Martin (2010), drivers perform more lane changes when this system is available as they seem to be more comfortable with a system that warns them when they are changing lanes. This increase in lane change maneuvers could lead to overall higher average speeds for the traffic stream, and increased throughput. On the other hand, Martin (2010) also concluded that when ACC was also available, the numbers of maneuvers decreased even when the LCA was available.

Since the actions and decisions associated with the LCA system affect mostly the driver, it is very difficult to incorporate them into a traffic simulator which replicates the expression of those actions in terms of vehicle movement. It is however possible to replicate the results of those actions, if the impact of the system is known, or can be assumed with some confidence. The hypothesis used in order to test this technology is based on the findings of Martin (2010) which indicate that drivers utilizing the LCA would perform more lane changes and decrease their lane change duration as a result of the LCA technology. In general, Martin (2010) found that drivers would perform discretionary lane changes in a more aggressive manner.

In order to replicate the LCA, a sensitivity analysis was performed with CORSIM to identify parameters that affect the number of lane changes performed and the duration of the maneuvers for discretionary lane changes. These are the lane changes performed when drivers are seeking an advantage over their current position and lane. In the field, this system can work in every roadway environment, but due to restrictions in CORSIM, it was only tested on freeway sections (FRESIM). The lane change parameters available for performing a sensitivity analysis within FRESIM environment are presented in Figure 3-4.

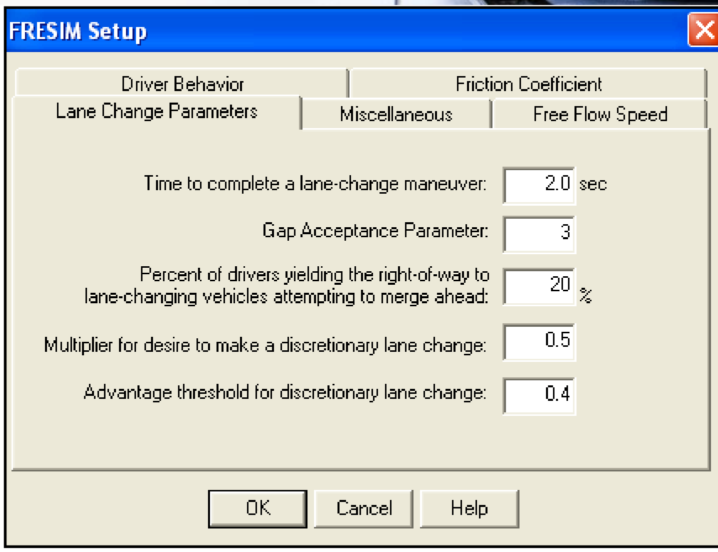

Figure 3-4. Lane Change Parameters for FRESIM

The multiplier for desire to make a discretionary lane change, and the advantage threshold for discretionary lane change (this value is the minimum that the advantage factor of a vehicle should achieve in order for this vehicle to attempt a lane change) are the two parameters related to the impacts of the LCA. Table 3-1 exhibits the total number of lane changes by link observed in a simulated test network for different values of these two parameters. The numbers shown is red are the default values. As expected, the higher the number for the multiplier for desire to make a lane change, the higher the total of lane changes performed. For the advantage threshold for discretionary lane change, the smaller this value, the more lane changes are performed.

Table 3-1. Sensitivity Analysis to Explore LCA Impacts on Traffic

FRESIM		Number of lane changes		
		Link1	Link 2	Link 3
Multiplier for desire to make a lane change	0.2	211.5	1065.4	312.2
	0.4	265.9	1178.6	387.0
	0.5	289.9	1183.8	404.4
	0.6	304.4	1258.4	439.3
	0.8	338.3	1305.3	465.1
	1	331.6	1350.1	478.6
Advantage threshold for discretionary lane change	0.1	455.9	1503.5	788.9
	0.2	381.8	1384.0	609.8
	0.3	329.9	1291.1	488.3
	0.4	289.9	1183.8	404.4
	0.5	261.3	1153.9	373.0

In order to replicate the impacts of the LCA, time to complete a lane-change maneuver was decreased to 1.5 sec (the default in CORSIM is 2.0 sec), the multiplier for desire to make a discretionary lane change was increased to 0.7 and the advantage threshold for discretionary lane change was decreased to 0.3. These parameter values were assumed and should not be seen as absolute values, but as relative changes to satisfy the assumptions regarding changes in driver behavior when LCA is available.

CHAPTER 4 EVALUATION USING CORSIM

The two algorithms described in the previous section were tested in CORSIM based on the network illustrated in Figure 4-1. This network consists of a freeway (gray lines in Figure 4.1) with a bottleneck in each direction (indicated by the red circles). There are four detectors placed on the freeway section, as illustrated in Figure 4-1. The freeway section was used to test the ACC and the LCA systems separately and in combination. For the ACC, if the vehicle had the technology, this system was active all the time along the freeway. The black lines in Figure 4-1 represent the surface streets and the two systems were not operational along those sections.

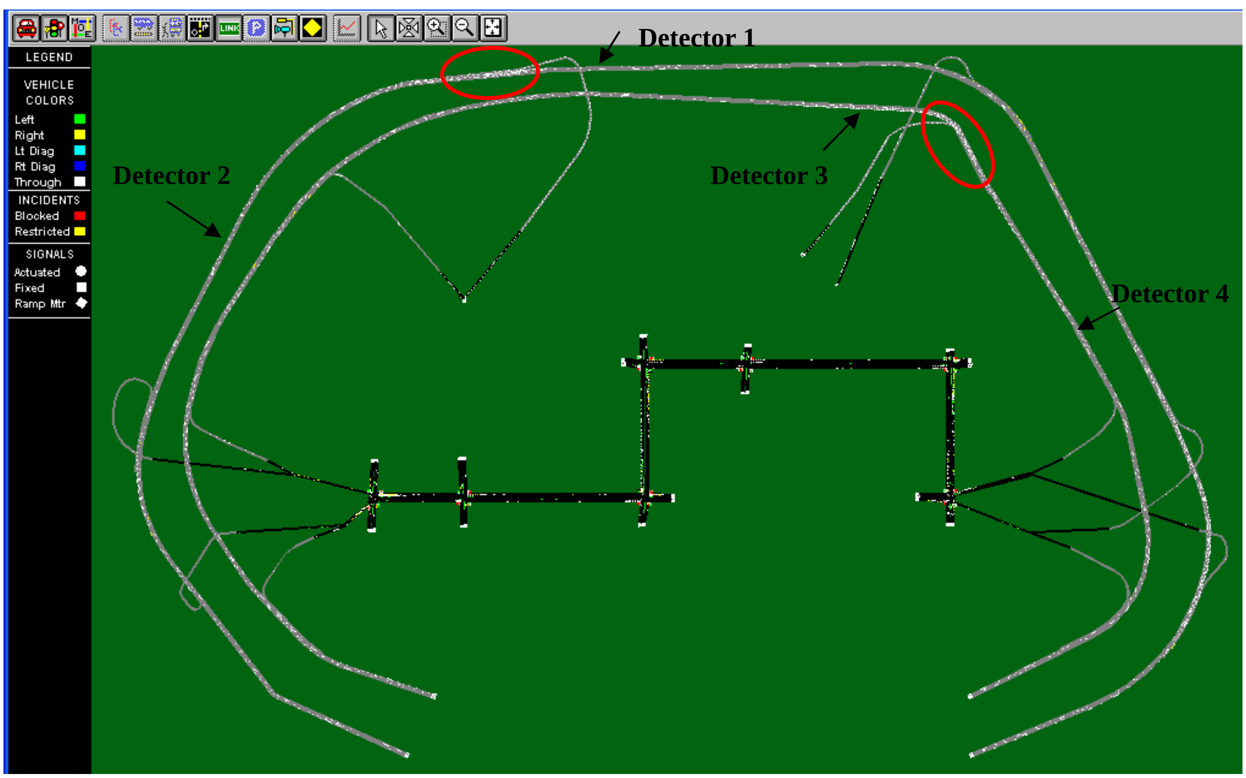

Figure 4-1. Illustration of the Test Network

Three scenarios were tested to evaluate the impacts of the technologies under various demands, and there were three time periods for each scenario, with duration of 900 seconds each. The "average demand" scenario had freeway entry demands ranging from 1,400 to 1,800 veh/hr/lane, and arterial entry demands ranging from 300 to 400 veh/hr/lane. The "heavy demand" scenario had freeway entry demands from 1,900 to 2,200 veh/hr/lane, and arterial entry demands from 400 to 500 veh/hr/lane. The "congested" scenario had freeway entry demands from 2,200 to 2,500 veh/hr/lane, and arterial entry demands from 550 to 650 veh/hr/lane. In each scenario, the first time period had the lowest volume. In the second period the demand was increased by 20 - 30%, while during the third period the demand decreased by 10-15%.

All scenarios use only passenger cars in the direction of detectors 1 and 2, while the other direction of the freeway had 20% heavy vehicles. The required number of runs for each scenario was estimated based on the average speed in the network. With a desired confidence at 95%, tolerance of 1 mile/hour and estimated standard deviation of 2.2 miles/hour^2, the total number of runs performed for each scenario was 20.

The maximum initialization time for the simulation was 20 minutes. The seed number for vehicle generation and response to traffic choices was varied (generated randomly by CORSIM), while the random number seed for vehicle entry headway was kept constant in all runs, to minimize variability due to the traffic demand. For all the scenarios, the CORSIM default values were used unless otherwise noted.

The car-following model adapted to incorporate ACC was implemented in CORSIM through a new dll file. This new version of CORSIM requires that the percentage of ACC vehicles is specified in record type 50 as shown in the example below:

```
8001  701900  20   0  100   100                              34 33 33         50
```

The number in red represents the percentage of ACC-equipped vehicles entering the network at a specific location (node 8001 in this example).

The time headway selected by drivers as an ACC requirement was added in record type 68 as a distribution through driver type and it ranges from 2.0 sec to 0.6 sec. The exact distribution applied to these tests is shown below:

```
200 184 168 153 138 122 106  91  75  60       1                              68
```

The scenarios were run first to evaluate the market penetrations of ACC. The base case was 0%, and there were three other cases used for comparison: 20%, 50% and 100%. The LCA was evaluated with a market penetration of 100% for all three scenarios for 0% and 100% of ACC vehicles. Table 4-1 summarizes the scenarios tested. There is a total of 18 different scenarios: the base case and the five market penetration scenarios tested for each of the three demand levels.

Table 4-1. Overview of the Scenarios Tested

Scenarios	ACC	LCA	
Average demand, Heavy demand, Congested	0%	0%	Base
	20%	0%	test 1
	50%	0%	test 2
	100%	0%	test 3
	0%	100%	test 4
	100%	100%	test 5

CHAPTER 5 DATA ANALYSIS AND RESULTS

This chapter summarizes the results obtained through CORSIM outputs first for the ACC, and then for the LCA separately and together with the ACC. In order to observe ACC impacts, the four detectors shown in Figure 4-1 provided averages of the headway (seconds), occupancy (%), speed (miles/hour) and volume (vehicles/hour). For the LCA, the total number of lane changes for the freeway was used to assess performance at each detector station. The network-wide effects (freeway only) of each of the two technologies separately and in combination were also assessed using the total travel time (hours) and the total miles traveled.

ACC

The impacts of ACC are presented for every scenario (average demand, heavy demand and congested) by detector (detector numbers shown in Figure 4.1), comparing the different levels of ACC market penetration (0%, 20%, 50% and 100%). The averages of selected performance measures are provided for every detector, along with graphs that illustrate how speed evolved during the three time periods tested. Detectors 1 (upstream of the bottleneck) and 2 (downstream of the bottleneck) represent flows with no heavy vehicles, while detectors 3 (upstream of the bottleneck) and 4 (downstream of the bottleneck) represent flows with 20% heavy vehicles.

For the average demand scenario, although the demand increases during the three time periods (second time period has the highest demand, with a small decrease in the third one, still higher than the first time period) there is no congestion. Figure 5-1 and Table 5-1 show that at Detector 1, the increase in the percentage of ACC vehicles does not affect the average speed, but it leads to a small volume decrease, due to longer headways (average headway with 0% penetration is 2.37 sec., while with 100% penetration it is 3.45 sec). There is a minor difference among headways for 20%, 50%, and 100% that is not shown in Table 5.1 because of rounding to the second decimal.

From Figure 5-2, detector 2 has slightly higher speeds at the first time period when ACC is present; therefore the average speed is also higher for the ACC scenarios. Table 5-2 shows that there is a decrease in volume of approximately 250 veh/hour (similar to detector 1). Overall, the results from detectors 1 and 2 (both in the westbound direction) are similar.

In the eastbound direction, the results from Detector 3 shown in Figure 5-3 and Table 5-3 are similar to the previous two detectors, despite the presence of trucks. Speeds are higher during the first time period when ACC is present, and there is an overall decrease in throughput even with small market penetration (20%). The results from Detector 4 (Figure 5-4 and Table 5-4) are also very similar, with an increase in the average time headway and average speed, and a decrease in occupancy and throughput.

The next set of graphs show the results from each of the four detectors for the heavy demand scenario. For detectors 1 and 2 in the westbound direction there is no congestion observed, and the results are similar to those under average demand; there is still no congestion. The results for detector 1 are shown in Figure 5-5 and Table 5-5, while those for detector 2 are shown in Figure 5-6 and Table 5-6.

Average Demand Scenario

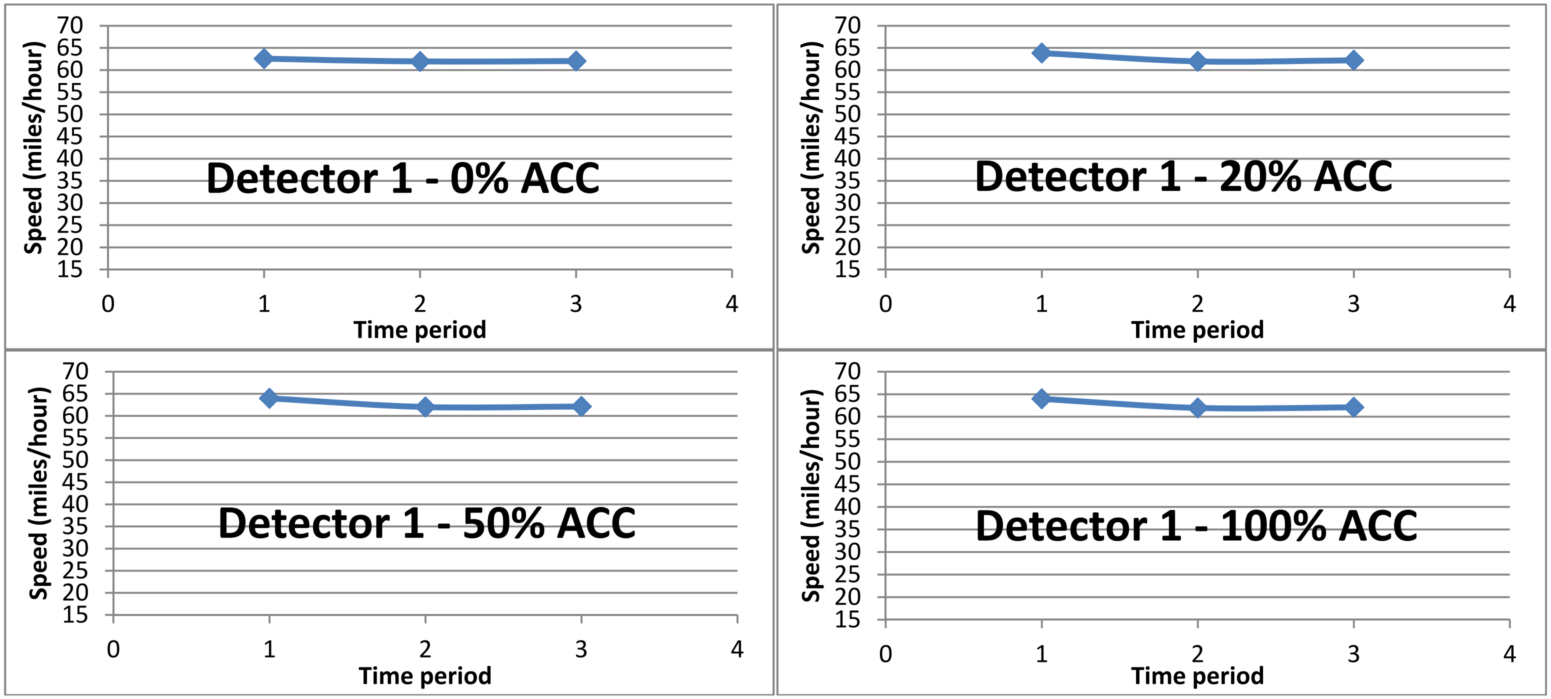

Figure 5-1. Speed versus Time Period Graphs for Detector 1, Average Demand Scenario

Table 5-1. Average Performance for Detector 1, Average Demand Scenario

Detector 1	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	2.37	8.94	62.18	1531.47
20%	3.45	7.31	62.66	1255.00
50%	3.45	7.27	62.70	1251.33
100%	3.45	7.26	62.67	1248.73

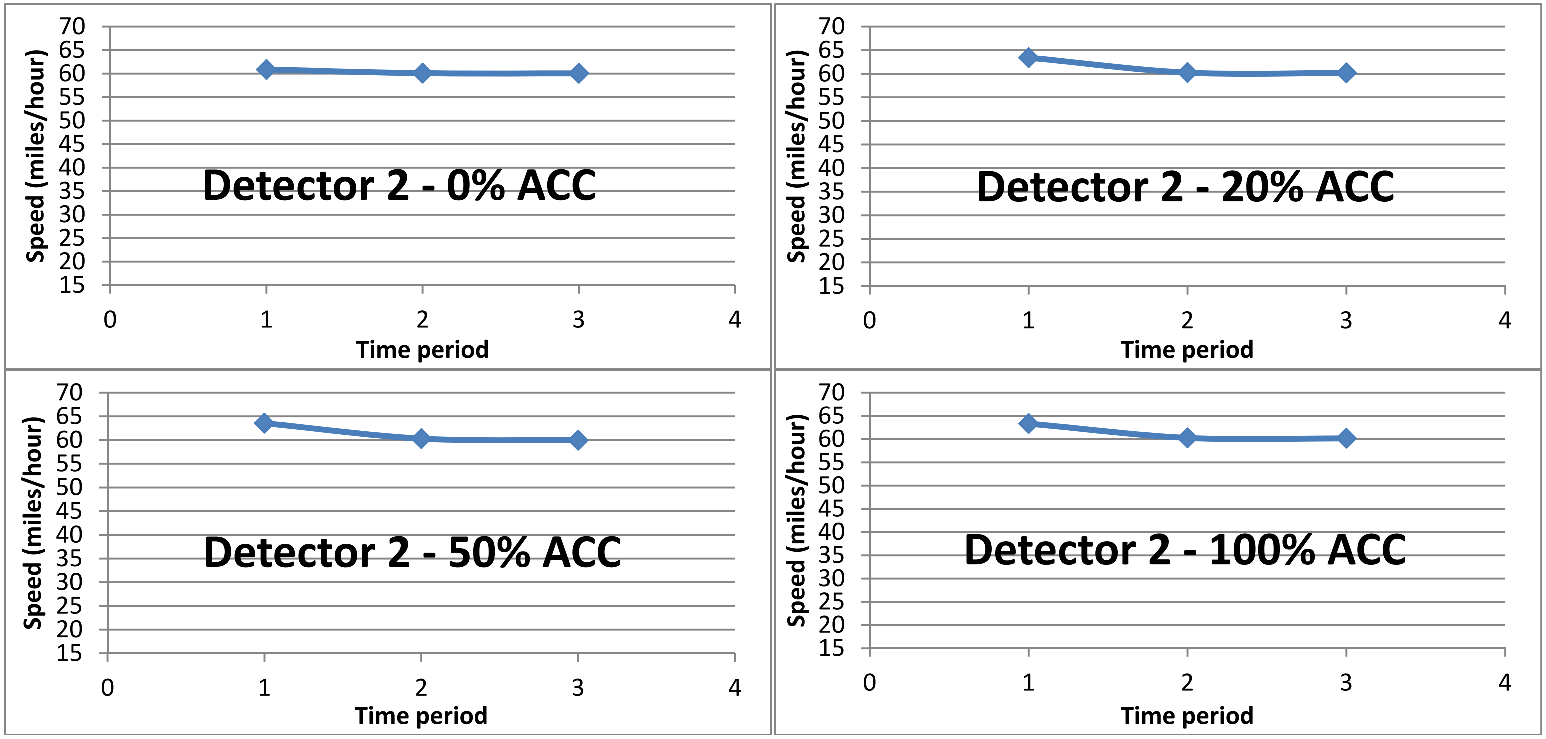

Figure 5-2. Speed versus Time Period Graphs for Detector 2, Average Demand Scenario

Table 5-2. Average Performance for Detector 2, Average Demand Scenario

Detector 2	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.69	12.79	60.35	2134.27
20%	1.99	11.19	61.28	1886.33
50%	1.99	11.23	61.28	1892.53
100%	1.99	11.22	61.26	1888.73

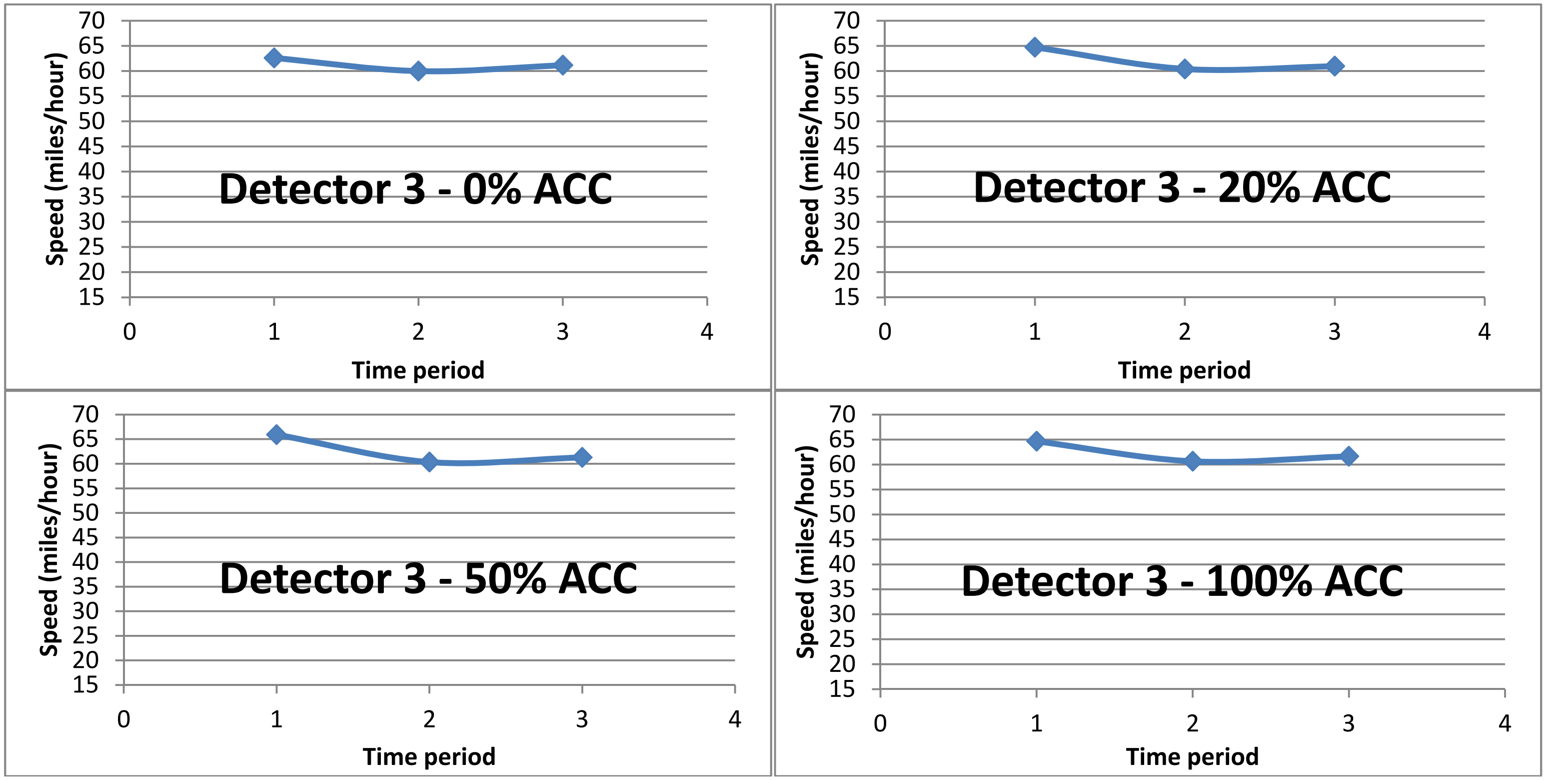

Figure 5-3. Speed versus Time Period Graphs for Detector 3, Average Demand Scenario

Table 5-3. Average Performance for Detector 3, Average Demand Scenario

Detector 3	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	2.30	11.37	61.24	1576.80
20%	3.49	9.12	62.02	1270.47
50%	3.55	8.98	62.52	1263.73
100%	3.55	8.97	62.31	1267.27

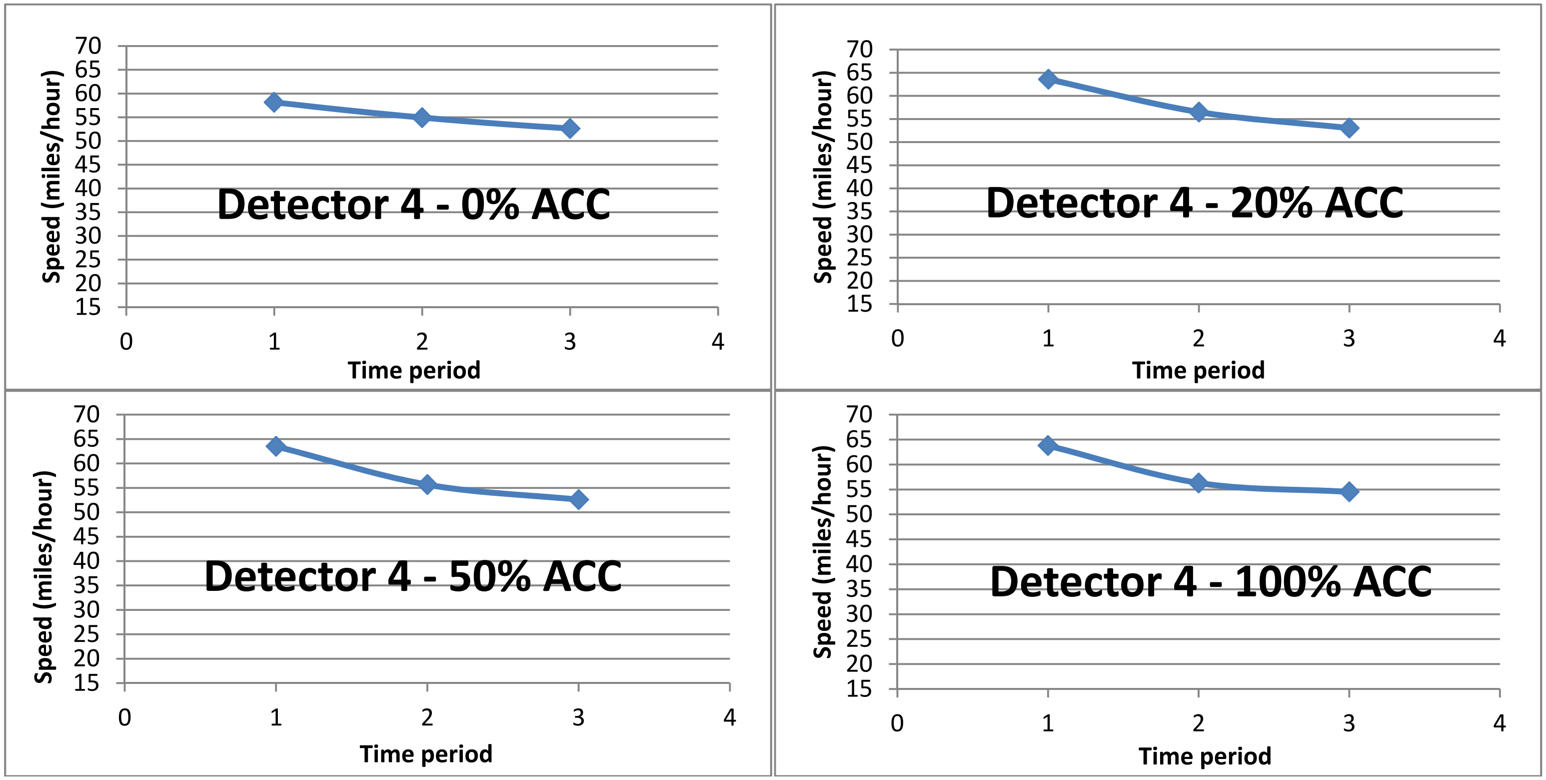

Figure 5-4. Speed versus Time Period Graphs for Detector 4, Average Demand Scenario

Table 5-4. Average Performance for Detector 4, Average Demand Scenario

Detector 4	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.71	17.31	52.61	2107.27
20%	2.11	13.99	57.70	1802.00
50%	2.09	14.48	57.25	1822.73
100%	2.08	13.76	58.21	1827.40

Heavy Demand Scenario

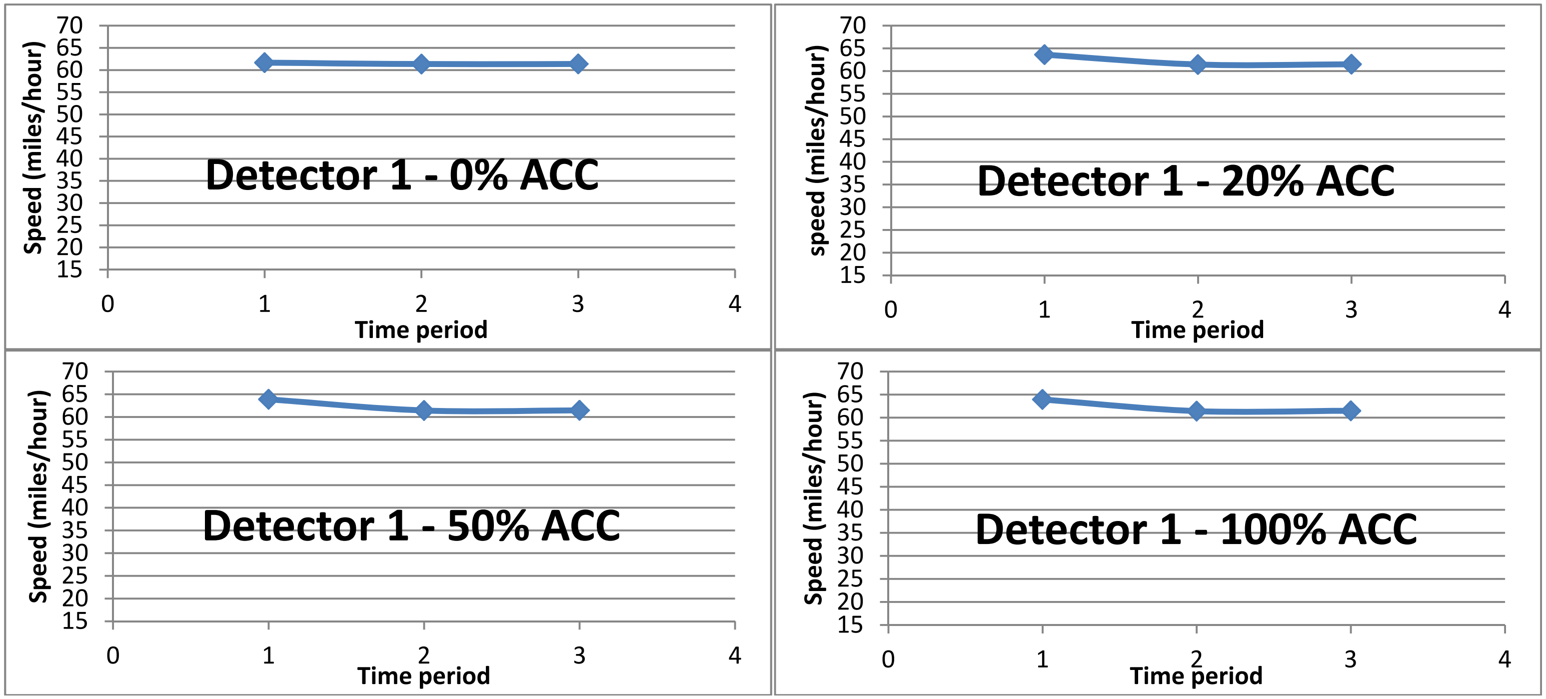

Figure 5-5. Speed versus Time Period Graphs for Detector 1, Heavy Demand Scenario

Table 5-5. Average Performance for Detector 1, Heavy Demand Scenario

Detector 1	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.92	11.06	61.46	1877.67
20%	2.80	8.82	62.19	1508.07
50%	2.78	8.88	62.26	1513.87
100%	2.79	8.85	62.30	1509.40

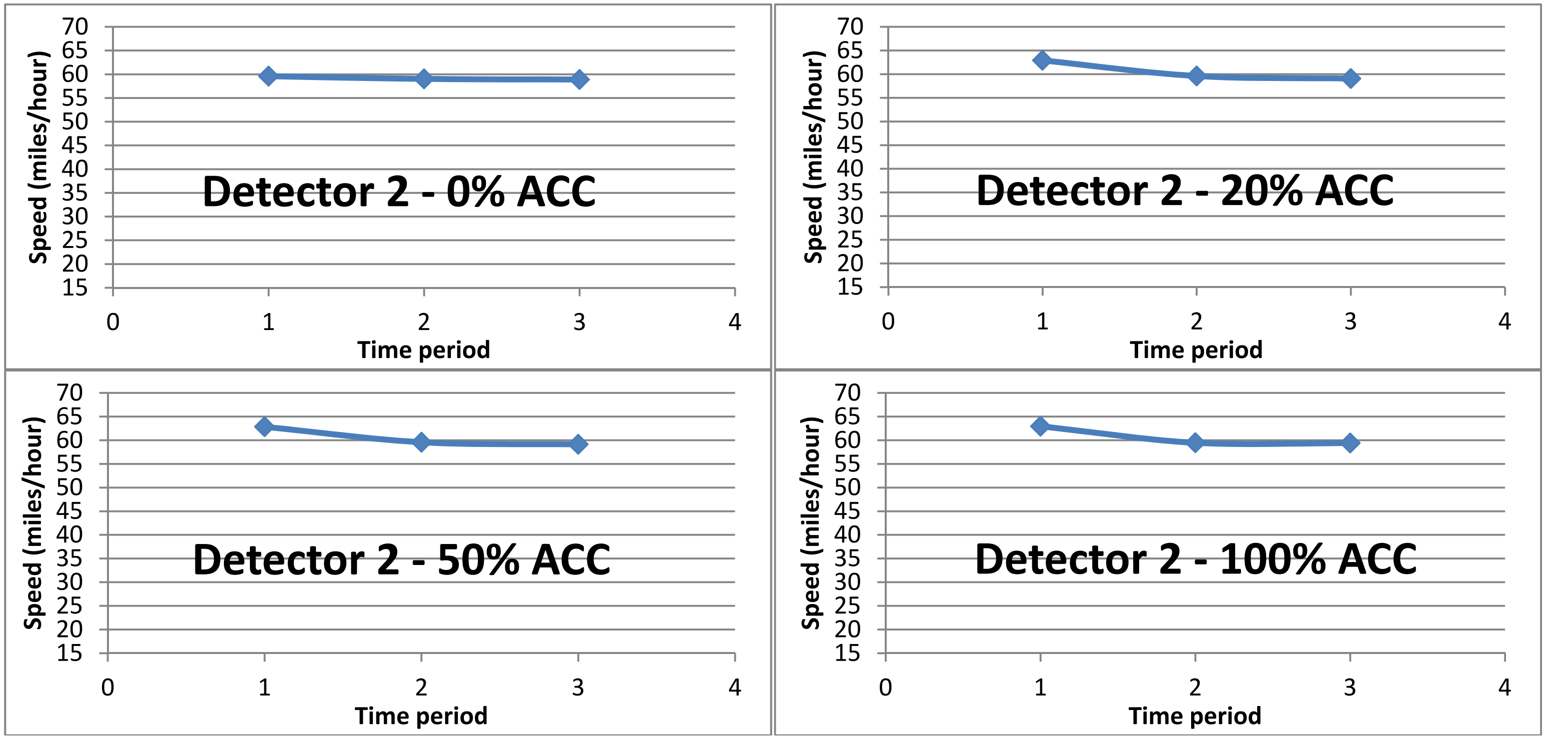

Figure 5-6. Speed versus Time Period Graphs for Detector 2, Heavy Demand Scenario

Table 5-6. Average Performance for Detector 2, Heavy Demand Scenario

Detector 2	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.50	14.63	59.17	2397.13
20%	1.81	12.42	60.53	2069.00
50%	1.81	12.46	60.51	2073.00
100%	1.81	12.45	60.60	2068.80

However, during this scenario there is congestion observed at detector 3, and a queue forms at the merge bottleneck after the first time period. Figure 5-7 and Table 5-7 present the results for this detector. As shown, for the 0% ACC, the speed drops to approximately 40 mph during the second and third time periods. This seems to be a result of the demand and the geometry of the roadway, and tests with and without trucks showed small differences. For the scenarios with ACC, the speed during the first time period is generally higher by nearly 10 mph, and only slightly higher (by 2-4 mph) for the second time period. During the third time period the speed is much lower when ACC is present, even for the 20% market penetration. The volume decrease is comparable to previous scenarios, however occupancy and speed are at the same levels as when ACC is not available.

The results from detector 4 under the heavy demand scenario are shown in Figure 5-8 and Table 5-8. The speed during the first and second time periods is higher by approximately 15 mph when ACC is present. However, during the third time period, the speed is lower with ACC than without, and it reaches 27 mph (vs. 35 mph with ACC). After watching the animation, it was observed that a bottleneck forms downstream at the on-ramp, because the ACC is not available on the surface network. Because of the specific combination of demands and geometry, the bottleneck forms only in the scenarios with ACC. Overall, speed is higher for all ACC scenarios, while throughput and occupancy are lower (Table 5-8).

In the congested scenario, the on-ramp in the vicinity of detector 1 becomes a bottleneck, and congestion is present throughout the three time periods. The presence of ACC leads to a drastic increase in the speeds regardless of the market penetration (Figure 5-9). Similar to the lower demand scenarios, there is a volume decrease of approximately 220 - 250 vph (Table 5-9), and there is a very significant drop in occupancy (more than 30%).

Detector 2 does not experience congestion and thus the pattern of speed changes is similar to that in the lower demand scenarios: there is a slight increase in speed during the first time period, while speeds are similar to the no-ACC scenarios. One difference to the lower demand scenarios is that when ACC is present the throughput is not reduced significantly (less than 100 vph). Compared to the heavy demand scenario, the volume for the no-ACC scenario is lower, but the throughput is maintained at a high level when ACC is present. This might occur because the bottleneck at detector 1 acts as a meter, lowering the demand that arrives at this detector. The lower headways with ACC at this location might occur because vehicles discharging from the upstream bottleneck still maintain lower headways when arriving at this location.

At detector 3, congestion is severe when there is no ACC, and speed is approximately 15 mph for all three time periods (Figure 5-11). When ACC is added conditions improve dramatically. Speeds increase dramatically during the first time period, and they remain higher than the no-ACC scenario for the duration of the simulation. Overall, occupancy is significantly reduced, and throughput slightly reduced when ACC is added (Table 5-11).

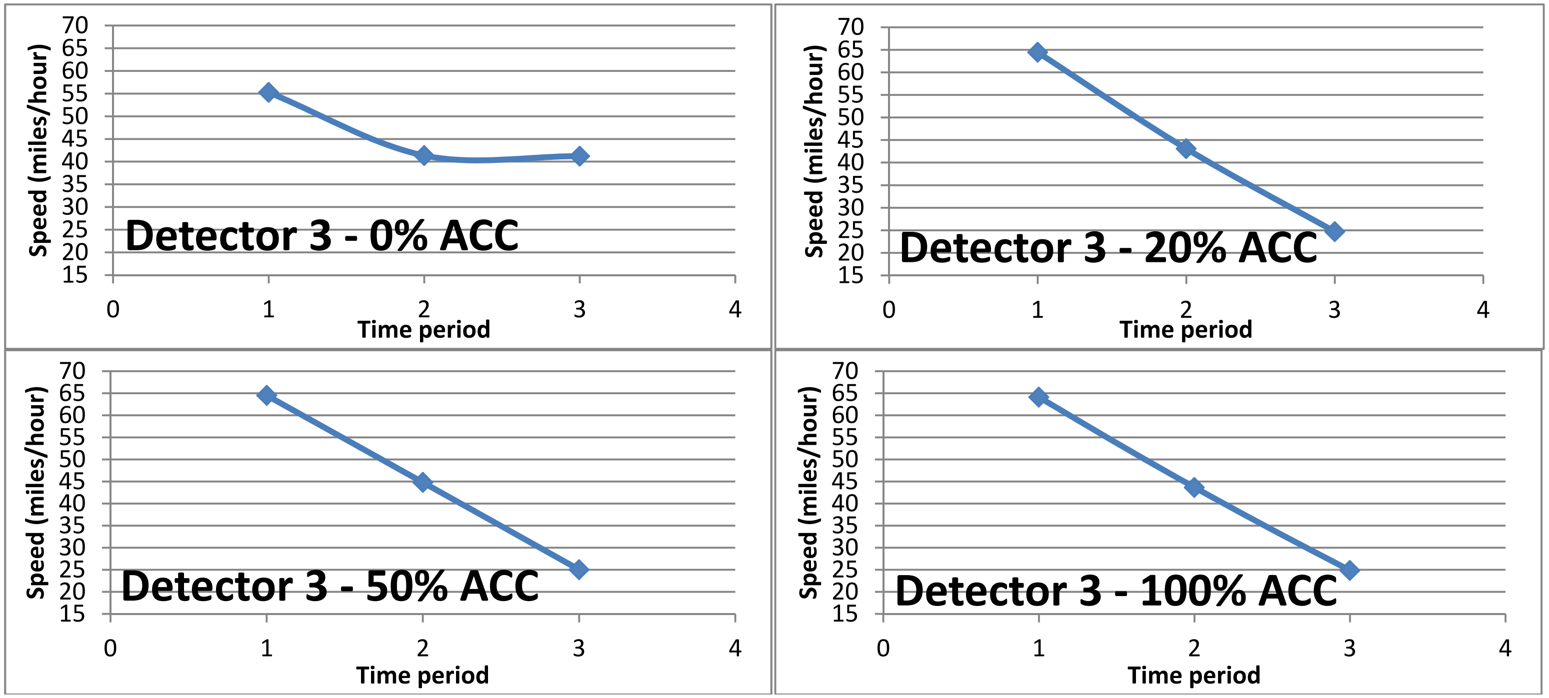

Figure 5-7. Speed versus Time Period Graphs for Detector 3, Heavy Demand Scenario

Table 5-7. Average Performance for Detector 3, Heavy Demand Scenario

Detector 3	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	2.01	21.85	45.94	1829.80
20%	2.78	21.92	44.08	1542.87
50%	2.79	21.46	44.79	1538.13
100%	2.77	21.69	44.20	1539.80

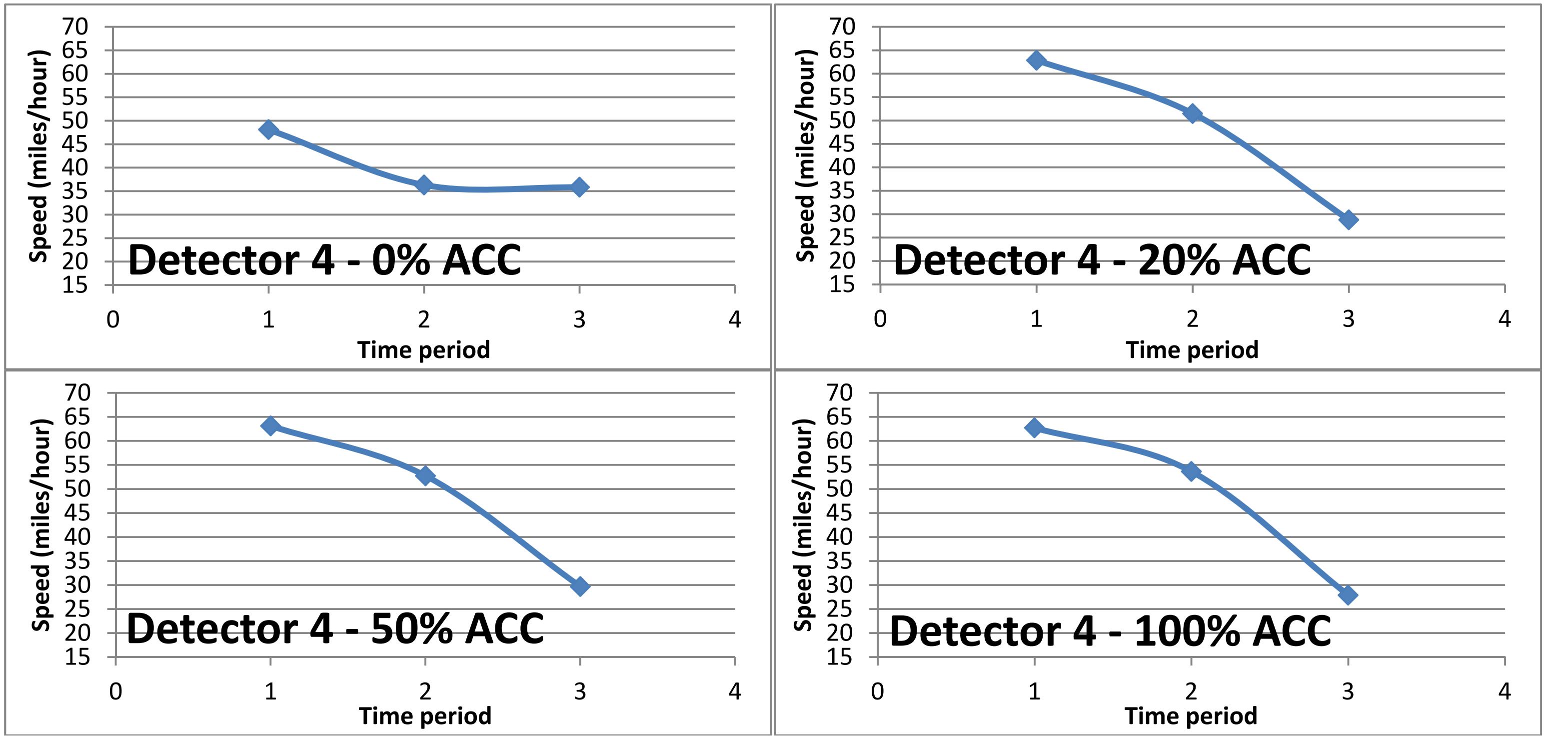

Figure 5-8. Speed versus Time Period Graphs for Detector 4, Heavy Demand Scenario

Table 5-8. Average Performance for Detector 4, Heavy Demand Scenario

Detector 4	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.62	29.76	40.09	2230.13
20%	1.92	22.69	47.71	1946.60
50%	1.93	22.17	48.52	1949.47
100%	1.92	22.46	48.09	1956.33

Congested Scenario

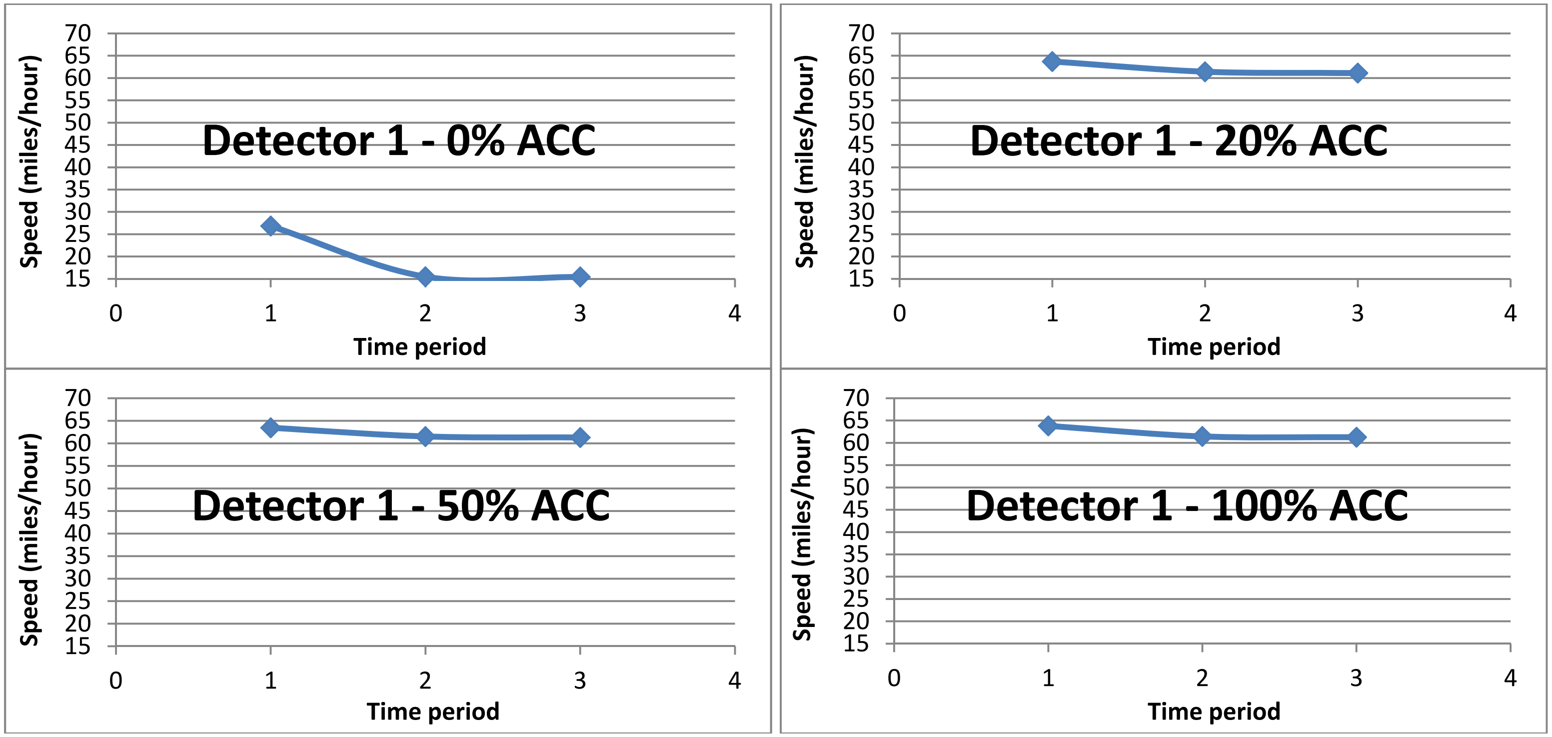

Figure 5-9. Speed versus Time Period Graphs for Detector 1, Congested Scenario

Table 5-9. Average Performance for Detector 1, Congested Scenario

Detector 1	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	2.03	42.07	19.25	1776.67
20%	2.69	9.15	62.09	1559.07
50%	2.71	9.08	62.09	1548.33
100%	2.69	9.10	62.18	1551.93

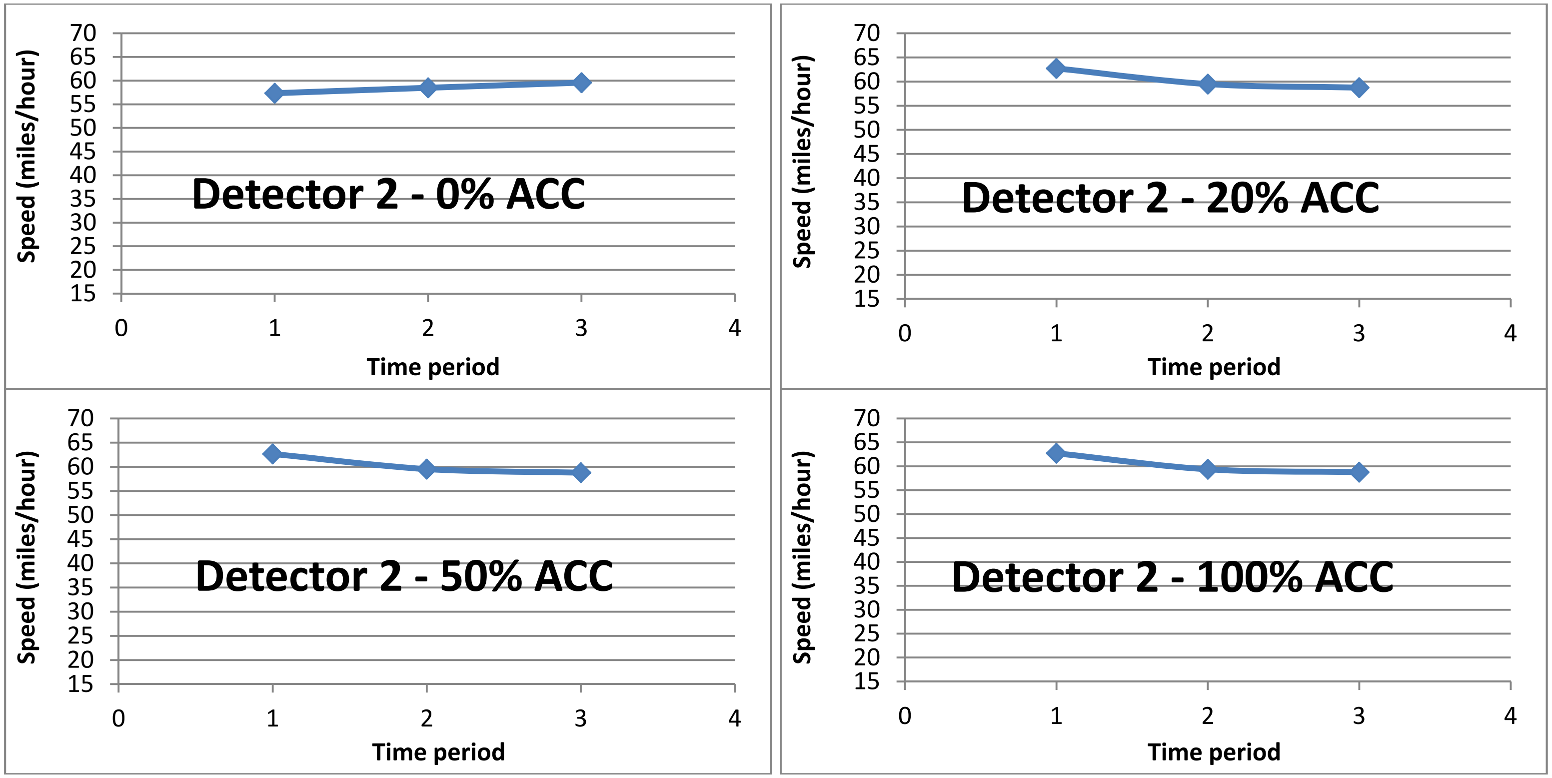

Figure 5-10. Speed versus Time Period Graphs for Detector 2, Congested Scenario

Table 5-10. Average Performance for Detector 2, Congested Scenario

Detector 2	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.65	14.52	58.45	2187.13
20%	1.79	12.67	60.32	2100.93
50%	1.78	12.67	60.32	2101.53
100%	1.79	12.70	60.29	2104.60

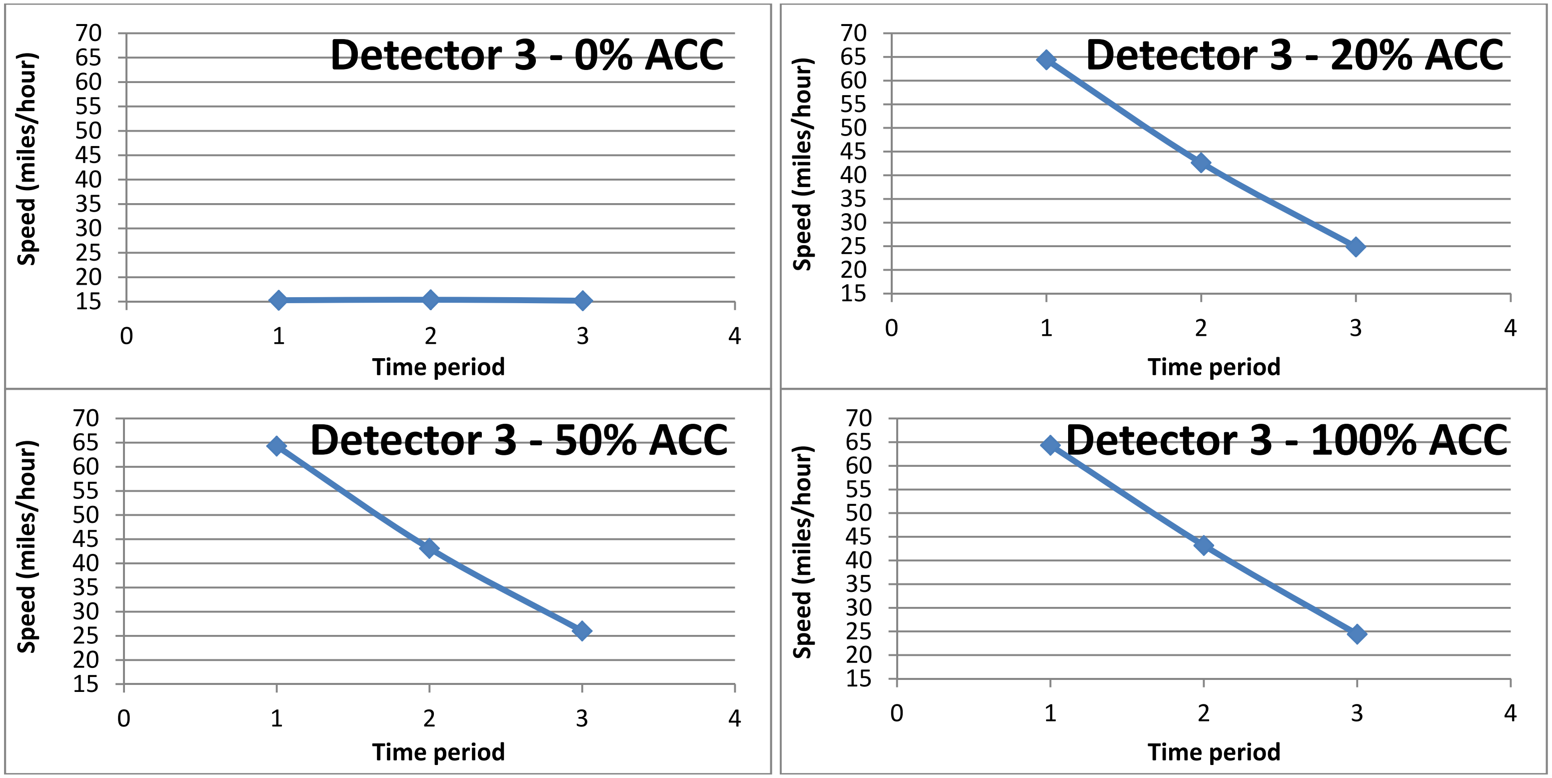

Figure 5-11. Speed versus Time Period Graphs for Detector 3, Congested Scenario

Table 5-11. Average Performance for Detector 3, Congested Scenario

Detector 3	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	2.26	46.11	15.28	1595.13
20%	2.69	22.17	43.98	1559.00
50%	2.69	21.63	44.46	1561.33
100%	2.71	22.17	43.98	1552.27

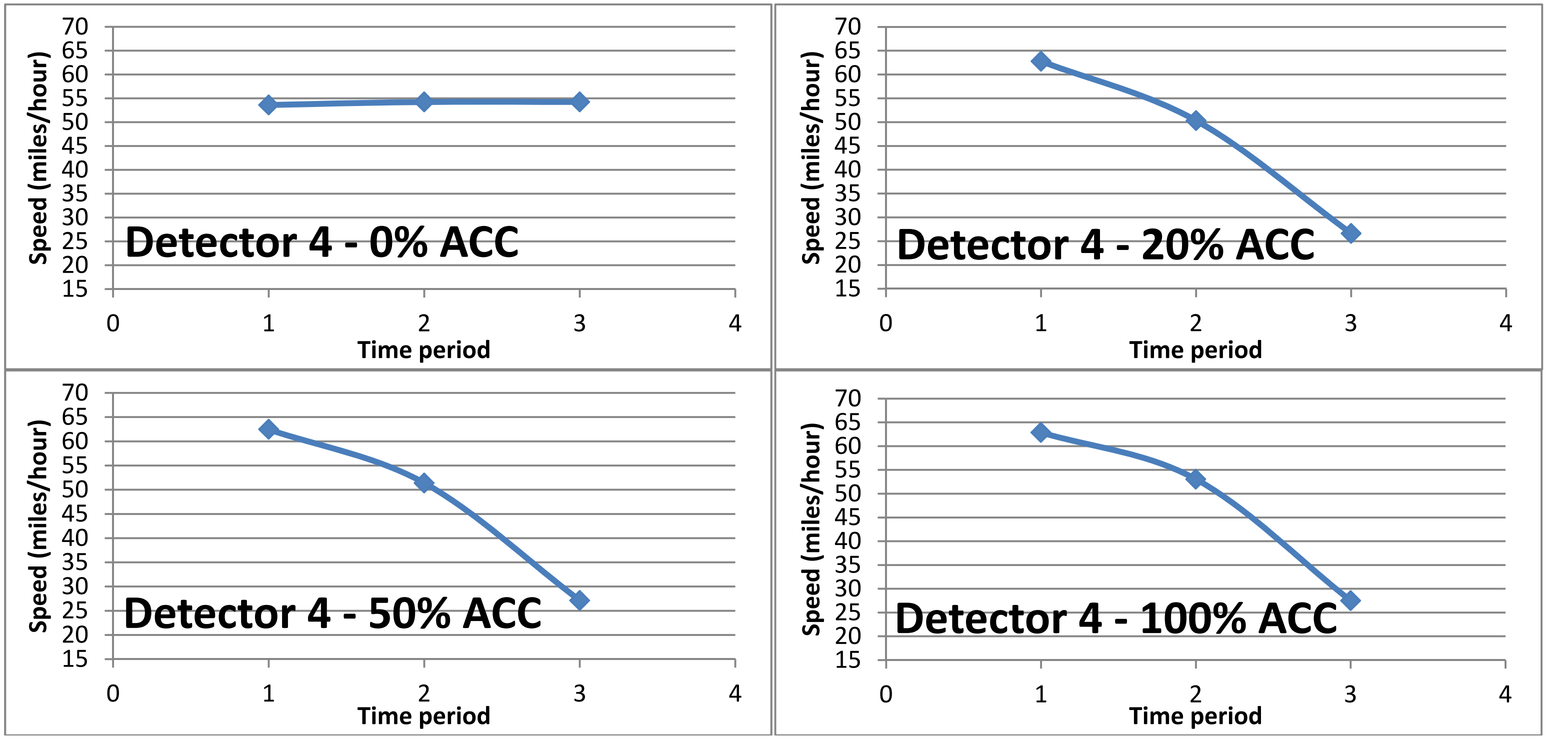

Figure 5-12. Speed versus Time Period Graphs for Detector 4, Congested Scenario

Table 5-12. Average Performance for Detector 4, Congested Scenario

Detector 4	Headway(seconds)	Occupancy (%)	Speed (miles/hour)	Volume (vehicles/hour)
0%	1.85	15.62	54.03	1948.13
20%	1.92	23.68	46.58	1946.20
50%	1.91	23.32	47.00	1957.40
100%	1.91	22.88	47.81	1952.93

Detector 4 has the same behavior as for the heavy demand scenario. A bottleneck is formed at the off-ramp, only when ACC is introduced. The speeds in the no-ACC scenario remain constant. When ACC is present speeds during the first time period are higher, and they gradually reduce during the second and third time periods, when spillback occurs (Figure 5-12). The throughput does not change significantly when ACC is introduced (Table 5-12).

To evaluate the network-wide effects of ACC the total travel time and the total vehicle miles traveled (VMT) for each demand and market penetration scenario are shown in Table 5-13 and Table 5-14. Overall, the total travel time decreases when ACC is present for all demand scenarios. The decrease is most dramatic for the congested scenario, where travel time decreases by approximately 50% even for the lowest market penetration. The results are consistent with the detector results, which generally indicate most significant improvements for the higher demand cases.

VMT decreases for all demand scenarios when ACC is introduced. Again, this is consistent with the detector results which indicate that there is lower throughput when ACC is present.

Table 5-13. Total Travel Time (hours) for the Entire Freeway Network with ACC

		0% ACC	20% ACC	50% ACC	100% ACC
Total Travel Time (Hours)	AVERAGE	200.08	168.72	169.24	168.17
	HEAVY	275.84	232.02	232.20	233.90
	CONGESTED	463.03	244.31	242.32	244.58

Table 5-14. Vehicle-miles travelled (VMT) for the Entire Network with ACC

		0% ACC	20% ACC	50% ACC	100% ACC
	MEDIUM	35024	29769	29800	29906
	HEAVY	38997	34638	34807	34814
Vehicle-miles travelled	CONGESTED	38165	36054	35815	36038

LCA and LCA with ACC

This section presents the results of the LCA tests, along with the results of tests combining LCA with ACC. Table 5-15 presents the total number of lane changes performed for each of the three demand scenarios, and three cases of market penetration of the LCA and the ACC. For all three scenarios the number of lane changes increases when only LCA is present. When ACC is also present, for average and heavy demands the number of lane changes decrease compared to the no-ACC case. This is consistent with the findings of Martin (2010) which showed in a driving simulator environmnent that the availability of ACC resulted in fewer lane changes.

Table 5-15. Total Number of Performed Lane Change Maneuvers for the Entire Freeway Network

		0%ACC-0%LCA	0%ACC-100%LCA	100%ACC-100%LCA
	AVERAGE	6603.35	7541.87	6607.22
	HEAVY	6946.55	8013.17	7013.95
Lane Changes Total	CONGESTED	5830.62	6653.58	7162.40

The network-wide effect of the combination of these systems is presented in **Error! Not a valid bookmark self-reference.** and in Table 5-17, where total travel time and VMT are compared among scenarios and among different percentages of both technologies. It can be concluded that the presence of LCA does not affect significantly the total travel time in the network, and there is even a slight increase for the heavy demand scenario. It is the ACC that leads to less total travel time in all cases, with the most significant improvement observed for the congested scenario.

LCA by itself was found to increase VMT for the heavy and congested demand scenarios, most likely because it increased the lane changes for those scenarios. However, when ACC is added, the increased time headway and reduced throughput counteract any effects LCA would have, and the VMT is reduced.

Table 5-16. Total Travel Time (hours) for the Entire Freeway Network with ACC and LCA

		0%ACC-0%LCA	0%ACC-100%LCA	100%ACC-100%LCA
Total Travel Time (Hours)	AVERAGE	200.08	200.17	168.42
	HEAVY	275.84	280.19	231.35
	CONGESTED	463.03	450.89	242.05

Table 5-17. Vehicle-miles travelled (VMT) for the Entire Freeway Network with ACC and LCA

		0%ACC-0%LCA	0%ACC-100%LCA	100%ACC-100%LCA
Vehicle-miles travelled	MEDIUM	35024	34982	29858
	HEAVY	38997	40446	34902
	CONGESTED	38165	38400	36207

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Advanced driver assistance technologies are continuously being developed to enhance traffic safety. Evaluations of such technologies typically focus on safety and there has been limited research on the impacts of such technologies on traffic operations. Given the difficulty in observing such impacts in the real world, traffic simulation was used to replicate such technologies under various demand and market penetration scenarios. The project focused on ACC and LCA. These two systems were replicated in a microsimulator (CORSIM) and their impacts were reported separately and in combination along a test network.

The following were concluded from the research:

- The ACC resulted in slightly increased speeds for the lower demand scenarios, and in significant speed increases for congested conditions. Improvements are observed and congestion is eliminated even for the lowest market penetration scenario tested (20% ACC), which is consistent with findings by Kesting et al. (2008). Generally, the concept of constant time headways appears to be promising for reducing congestion.
- When ACC is present, bottlenecks can be created at the interface of facilities with ACC to facilities with out ACC. When such systems are implemented in the future, extra care should be taken in advance to address potential issues generated by these locations.
- The ACC resulted in a decrease in throughput for nearly all scenarios tested because the ACC produced on the average longer time headways. However, the selection of time headways under ACC was a user-defined input (range was from 0.6 to 2.0 sec) and a different distribution might result in slightly different throughput;

- When only the LCA was present the number of lane change maneuvers increased, the throughput (VMT) increased, and travel time was not significantly affected. When both LCA and ACC were present, conditions improved significantly, and similarly to when ACC was available by itself.

Generally, the research conducted here was useful as an initial evaluation, but it was based on some key assumptions which would need to be further explored. First, there was no consideration for drivers turning on and off their systems throughout the test network, and it was assumed that drivers with the technology would use it the entire time. In reality, this is not necessarily the case, as drivers may switch back and forth, with unknown impacts to the system.

Second, the desired time headway distribution selected by drivers in the field is not known. The distribution used in this project had a range of 0.6 to 2.0 sec (described in Chapter 4), and the results of the tests could be refined once driver preferences regarding their desired headways are known. A similar point can be made regarding the LCA: it is not known yet how drivers would use such systems in everyday traffic, and thus the assumptions used in the simulator would need to be revisited once field data are available.

Third, additional technologies such as the Cooperative Adaptive Cruise Control (CACC) should also be examined to evaluate their impact relative to ACC. Such impacts should be evaluated on a variety of highway environments, such as two-lane highways and arterials.

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APPENDIX A - Algorithms for vehicle without the technologies

Car following model in FRESIM

In order to determine the acceleration of the follower vehicle, FRESIM employs the Pitt car-following model. The notation used to apply this car-following model is provided below:

k car following parameter (driver sensitivity)

L length of the leading vehicle

T scanning interval

a acceleration of the follower in the interval (t, t+T)

b constant

c lag (reaction time is always less than T)

e maximum emergency deceleration

x position of leader at time t

y position of the follower at time t

u speed of the leader at time t

v speed of follower at time t

x_1 position of leader at time t+T

y_1 position of follower at time t+T

u_1 speed of leader at time t+T

v_1 speed of follower at time t+T

The space headway that the follower tries to maintain is assumed to be:

$$L + 10 + kv + bk(u-v)^2$$

Note that we are given x_1, y_1, u, and v, and we need to calculate a. Also,

$$y_1 = y + vT + aT^2/2 \text{ and } v_1 = v + aT,$$

The desired position at time t+T is given by

$$x_1 - y_1 = L + 10 + kv_1 + bk(u_1 - v_1)$$

This becomes

$$x_1 -(y+vT+ aT^2 / 2) = L + 10 + k(v+aT) + bk(u_1 - v)^2$$

Note that $(u-v)^2$ is small and therefore v_1 is used as an approximation to v. Solving the above equation for a, we get,

$$a = 2[x_1 -y- L-10- v(k + T) -bk(u_1 -v)^2] / [T + 2kT]$$

This is the car-following relationship used by FRESIM. The term b is included to allow high relative closing speed behavior observed empirically, and has been calibrated to

$$b = 0.1 \text{ for } u.- v \leq 10$$
$$0 \text{ otherwise}$$

After including the driver reaction time c, the new position and speed are defined as

$$y_1= y + vT + a(T-c) / 2 \text{ and } v_1 = v + a(T-c), \text{ where } c < T.$$

Note that these car-following rules may be over-ridden by the emergency constraints to prevent collisions. The goal is for the follower to be able to stop safely before colliding with its leader if the leader stops suddenly, and also have its deceleration rate within the maximum deceleration emergency limits. By default, the maximum emergency deceleration for all vehicle types is -15 ft/sec/sec.

Lane changing model in FRESIM

There are two types of lane-changing maneuvers.

1. Mandatory lane changing

2. Discretionary lane changing

If the vehicle undergoes a lane-changing maneuver, it stays in the lane change condition for the duration of the hiatus period (default value is 2 seconds). Discretionary lane changes are inhibited during the hiatus period. Mandatory lane changing is not subject to the expiration of the hiatus period and may be performed in any time step in response to the downstream geometrics.

In order to perform a lane-changing maneuver, an acceptable lead gap and an acceptable trailing gap must be available in the target lane. Acceptance of the lead gap is modeled through the amount of the deceleration that is required by the lane changer to avoid collision with its putative leader in the target lane. The putative leader in the target lane is assumed to decelerate with the maximum possible deceleration and the required deceleration required by the lane changer in order to avoid collision is computed. This computed deceleration is compared to a computed acceptable deceleration which is called the acceptable lane changing risk. The lead gap is accepted if the required deceleration is smaller than the acceptable risk.

In order to avoid collision with the putative leader, the required deceleration is adjusted in the hiatus period to reflect the lane changer vehicle capability and the driver characteristics.

Assuming that the lane changer will travel for the duration of the hiatus period using the computed deceleration, the above process is repeated for the putative follower in the target lane. The required deceleration by the putative follower to avoid collision with the lane changer at the end of the hiatus period is compared to the risk of the acceptable follower. If the required deceleration is smaller than the acceptable risk, the trailing gap is reported as acceptable.

A vehicle with acceptable lead and trailing gaps initiates a lane change into the target lane.

Mandatory lane changing

A vehicle experiences mandatory lane changing under the following conditions:

1. Vehicle is traveling on an acceleration auxiliary lane and must vacate the lane to merge with the through traffic.
2. Vehicle is destined to exit the freeway and has passed an off-ramp advanced warning sign, but is not in the proper lane to exit the freeway.
3. Vehicle is traveling on a lane which will be dropped further downstream and has passed the lane drop advance warning sign.
4. Vehicle is traveling on a lane which is blocked through an incident blockage further downstream.
5. Vehicle wishes to enter an HOV lane and is not in a lane that leads to the HOV lane, or vehicle does not wish to use an HOV lane and is in a lane that leads to the HOV lane.

For mandatory lane changing, the acceptable risk is inflated as the need for lane changing becomes urgent.

For a vehicle traveling on an auxiliary lane, the acceptable risk takes a minimum value of -5 ft/sec/sec and is inflated using a functional form that varies as the square root of the distance to the end of the auxiliary lane. The maximum acceptable risk is -15 ft/sec/sec.

A vehicle destined to exit the freeway will accept a risk of -5 ft/sec/sec upon crossing the advanced warning sign and the risk is inflated as the square root of the distance left to the off-ramp as the vehicle moves towards its destination.

The acceptable risk for a vehicle approaching a lane drop starts at a minimum value of 5 feet as the vehicle crosses the lane drop warning sign, and is inflated as the square root of the remaining distance to the lane drop.

For the vehicle approaching the blockage incident, the acceptable risk begins at -5 ft/sec/sec as the vehicle passes the blockage warning sign. The user may not have defined an advanced warning sign for a blockage incident in which case the model puts an advanced warning sign at 1500 feet from the blockage. The risk is again inflated as the square root of the remaining distance to the incident blockage to a maximum of -15 ft/sec/sec as the vehicle approaches the blockage.

The acceptable risk for the putative follower in the target lane depends on whether or not the follower is cooperative. FRESIM assumes that a certain percentage of the drivers are cooperative during a lane changing process and this is determined stochastically. Cooperative drivers accept a risk of -15 ft/sec/sec and non-cooperative drivers assume a risk of -8 ft/sec/sec.

Discretionary lane change

Discretionary lane change is performed when a lane change indicates a speed advantage for the vehicle over its current position and lane. A vehicle that is traveling below its free-f1ow speed becomes a candidate for a discretionary lane change.

A vehicle considering discretionary lane changing is modeled on the following factors

1. Motivation
2. Advantage
3. Urgency

<u>Motivation</u>

The desire of a vehicle to perform a lane change is modeled as motivation. The model assumes that the degree of desire for the lane change is a function of the current speed and driver characteristic of the vehicle. To this effect, the model assigns an intolerable speed to the vehicle which is computed as follows:

VI = VF * (0.7 + DRVRC / 50.)

where

VI is the intolerable speed,

VF is the desired free-flow speed,

and DRVRC is the driver characteristic code.

The desire of the driver to make a lane change is then computed as

D = 1 -(V-VI)/(VF-VI)

where

D is the lane change desire in percentage, and V is the vehicle speed.

It is noted that a vehicle traveling below its intolerable speed will certainly desire a lane change and a vehicle traveling at or above it's desired speed will not desire a lane change. The desire factor is linearly interpolated for speeds between the intolerable and desired speeds.

Advantage

For a vehicle desiring a lane change, the advantage logic determines whether or not there is any benefit to this lane-changing maneuver. Advantage in lane changing is modeled using two factors:

1. Lead factor (FL)
2. Putative factor (FP).

Lead factor represents the disadvantage associated with staying in the current lane with respect to the current leader of the vehicle. To compute the lead factor, existing headway in the current lane of the vehicle is computed as

$$H = (DX + VC * DS) / VF$$

where

DX is the separation between the vehicle and its leader in the current lane,

VC is the speed difference between the vehicle and its leader in the current lane,

DS is the speed threshold factor, and

VF is the desired free-flow speed of the vehicle.

The lead factor, FL, is then computed as (H - Hmin) / (Hmax - Hmin) where

Hmin is the lower bound for headway in lane changing, (2 sec), and

Hmax is the upper bound for headway in lane changing, (5 sec).

Note that large values of the lead factor indicate that the lane changing is not beneficial to the driver. Note that at headways below the lower bound, it is extremely beneficial for the vehicle to perform a lane-changing maneuver. The advantage of performing a lane change decreases linearly as the headway increases.

The putative factor is the perceived gain in moving to the new lane. The logic computes the putative factor for both adjacent lanes. The lane with the largest putative factor is the target lane for a lane change.

The putative factors are calculated the same as the lead factor, except that the lead vehicle is replaced by the putative leader. There may be a left-side and/or a right-side putative factor. FP is the maximum of the putative factors.

The overall advantage factor (Adv) is then computed as

Adv = FP - FL

A vehicle with an advantage factor over a specified threshold value (default of 0.2) will attempt a lane change.

Urgency

Urgency models the intensity of the desire for lane changing. Urgency affects the acceptable risk in performing the lane change. Urgency model is built on the assumption that a vehicle which was motivated to perform a lane change in the past but could not do so, would gradually become impatient and feel the urgency to change lanes. This would happen at the cost of the vehicle willing to accept higher risks.

In order to compute urgency, the impatience factor of the driver is first computed. It relates the level of the desire to the past behavior of the driver using a moving average representation given by:

IMP(t) = IMP(t-1) + (DRVRC + 1) / 20.

where

IMP(t) is the impatience factor at time t,

IMP(t-1) is the impatience factor at the previous time.

The urgency for a lane change also depends upon the disadvantage of remaining in the current lane. The greater the disadvantage, higher the urgency for a lane change.

The urgency factor, U, is determined by

U = IMP(t) * (1- FL)

The acceptable risk for performing the lane change is then computed as

RISK = Rmin + (Rax - Rmin) * (U - UTH(DRVRC)) / (1 - UTH(DRVRC))

where

Rmin is the minimum acceptable risk, -5 ft/sec/sec,

Rmax is the maximum acceptable risk, -10 ft/sec/sec

UTH is the urgency threshold by driver type.

The urgency threshold depends upon the driver type and is computed as

1 - (DRVRC / 20)