Evaluation of Driver Assistive Truck Platooning on Traffic Flow

by

Mikhail Malcolm Gordon

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 1, 2015

Keywords: Platooning, Automation, CACC
DATP, Microsimulation, CORSIM

Approved by

Rod E. Turochy, Chair, Associate Professor of Civil Engineering
Jeffrey J. LaMondia, Assistant Professor of Civil Engineering
Chase C. Murray, Assistant Professor of Industrial & Systems Engineering

Abstract

Interest in driver assistive truck platooning (DATP) through the application of coordinated adaptive cruise control in the freight trucking industry is on the rise due to its expected benefits on the roadway. To investigate traffic flow impacts, as part of a study sponsored by the Federal Highway Administration, a traffic microsimulation model is developed in CORSIM software. This simulation takes place on a segment of Interstate 85 in the Auburn, AL area. The parameters of headway, market penetration, and traffic volume are varied.

These results of simulation are analyzed using travel time benefit and average speed as the measures of effectiveness. The statistical significance of the simulation results are analyzed using both a t-test and multilevel ANOVA. An adequate choice for the implementation of DATP technology on the roadway with current traffic volume is found to be 1.00 second headway with greater than 20% market penetration.

Acknowledgments

I would like to first thank Dr. Rod Turochy. The many hours of guidance on not just this study but all the work I have accomplished at Auburn has proved to be essential. I would also like to thank Dr. Jeffrey LaMondia and Dr. Chase Murray for serving on my thesis committee. I would also like to thank Dr. David Bevly the principal investigator on the FHWA project that this research was included in.

I must also thank Dr. Overtoun Jenda and the Bridge to the Doctorate program, through which my graduate study was funded. The contributions of this program have allowed for my graduate study and also allowed for travel to conferences throughout my time at Auburn.

Lastly, I must thank my family for their support throughout this process. To my parents everything you instilled in me while growing up made this possible. I can never thank you enough.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AADT	Average Annual Daily Traffic
ACC	Adaptive Cruise Control
ALDOT	Alabama Department of Transportation
ANOVA	Analysis of Variance
CACC	Cooperative Adaptive Cruise Control
DATP	Driver Assistive Truck Platooning
DDHV	Directional Design Hourly Volume
DHV	Design Hourly Volume
FHWA	Federal Highway Administration
ITS	Intelligent Transportation Systems
NHTSA	National Highway Traffic Safety Administration
PHV	Peak Hour Volume
VMT	Vehicle Miles Traveled

Chapter 1 – Introduction

1.1 – Background

Roadways are complex systems that are necessary for moving both people and goods throughout the nation. Since the personal vehicle was introduced onto roadways in the United States the number of vehicles on roadways has increased. The number of vehicle miles traveled (VMT) on these roadways has also generally been increasing. In the twenty years from 1993 to 2013 the overall VMT increased approximately 30% from 2.29 trillion to 2.99 trillion (FHWA, 2013). This increase in miles traveled leads to delay on roadways that are not equipped to handle the traffic volumes they carry. Roadways are typically built for a traffic volume forecasted for a lifecycle ranging from 20 to 50 years but stay in service for a much longer time. In order to mitigate the resulting delay on roadways, there need to be changes to either the roadway itself or the traffic that uses the roadway. Changes to the roadway itself are usually capacity expansion projects. These are capital heavy projects that also lead to the roadway being out of commission or under a capacity reduction while the construction process is completed, thereby having adverse impacts on traffic. State transportation agencies will use these expansion projects to combat delay on roadways only when there is no other option.

These problems are nothing new to those in the transportation field and new technologies have been investigated to alleviate the problems of delay. Intelligent transportation systems (ITS) improve the safety and efficiency of roadways through the use of advancements in technology. This technology allows for drivers to have an increased amount of information about the roadways. One major focus area of ITS technology is on vehicles; this branch of ITS is often called intelligent vehicles. Intelligent vehicle technology is one of the fastest growing areas in transportation. The intelligent vehicle allows for new technologies such as collision avoidance, parking assistance, emergency braking, lateral control, and longitudinal control. Sensing technologies such as radar monitor the vehicle and its surrounding environment. Radar allows for the implementation of the technologies summarized above. Collision avoidance, parking assistance, and emergency braking are currently features found in luxury cars from companies such as Audi (Audi, 2011). The lateral and longitudinal control systems on vehicles allow for the speed and spacing of vehicles to be set on the roadway. The application of ITS technology allows for this is adaptive cruise control (ACC). Adaptive cruise control sets a following distance for the vehicle ahead and automatically adjusts its speed to keep at this distance (Wayland, 2015). This reduces the perception reaction time that is necessary for drivers to make decisions on the roadway. This should correspond to a decrease in the delay seen on the roadway. The use of adaptive cruise control has been beneficial and is currently used by many in the automotive industry. Audi implemented ACC in certain models of its vehicles in 2011 and it is now available in both the A and Q series vehicles (Audi, 2011). The technology is found in over 60 vehicles from the top five automakers in the United States (Wayland, 2015).

The ITS applications discussed above have a common goal of enhancing the automation of vehicles on the roadway to improve safety and efficiency of the system. The first automated vehicle was unveiled at Japan's Tsubaka Mechanical Engineering Laboratory in 1977 (Devitt et al., 2013). Dedicated research into automated vehicles has been accomplished since this time, and the advancement of computing resources has been extremely beneficial to vehicle automation. Automation has more recently been divided into a five-level concept (Shladover, 2012). Level 1 is driver-only control which is what has been on the roadways since the vehicle itself was invented. Level 2 is driver assistance in which the driver is mostly in control but one control task (longitudinal or lateral) is automated to a certain extent. Level 3 is partial automation in which the control is taken over but the driver must monitor the system, and be ready to take over control at any time. Level 4 is high automation in which the driver no longer needs to monitor the system; if a take-over is necessary the driver will be alerted. Level 5 is full automation in which the driver will never need to take-over (Shladover, 2012). Level 2 is currently seen on the roadway in application such as lane assist and blind spot monitoring. This study focuses on evaluating the impacts of another level 2 technology: cooperative adaptive cruise control (CACC), implemented in heavy-duty trucks.

Wireless technologies allow for short range communication between vehicles and also between a vehicle and the roadway, known as V2V and V2I respectively. For example, these communications allow for electronic toll collection that is done on roadways. The addition of wireless communication onto the already prevalent ACC systems gives added benefit to driver assistance systems. CACC technology allows for the following distance to be set similar to ACC, but also allows for the two vehicles to ‘speak’ to each other through wireless communication. This Dedicated Short Range Communication (DSRC) allows for vehicles to transfer location and speed on wireless controllers. Any sudden movements that must be taken by a lead vehicle will now automatically be accounted for by the following vehicle. CACC technology will be implemented in the near future and will allow many of the decisions that are now made directly by the driver to become automated.

To evaluate the effects of future CACC deployment on traffic, modeling of such traffic conditions using microsimulation software is a useful tool. Traffic microsimulation is the modeling of individual vehicles in order to assess the performance of a roadway system (Dowling et al., 2004). Microsimulation allows roadway agencies to analyze changes to roadway networks before their actual implementation. Microsimulation is a low cost analysis method and gives initial information about roadway networks that can then be optimized for the actual implementation. With emerging technologies such as CACC, the use of microsimulation can give added information about their potential impact to the overall traffic stream. Possible ways to quantify the impacts include the travel time delay and average speed of the network.

1.2 – Objectives

This thesis focuses on the estimation of traffic impacts of CACC technology, specifically on its application with heavy-duty trucking. This heavy-duty trucking application is also referred to as Driver Assistive Truck Platooning (DATP). This will be done by implementing a traffic microsimulation model to examine the efficiency impacts on a highway segment where heavy duty trucks have CACC capability. The main objectives of this research project are:

1. Develop a baseline traffic microsimulation of current conditions on a section of interstate highway;
2. Choose parameters to best investigate the implementation of CACC on roadways;
3. Develop microsimulation cases for varying cases of CACC parameters;
4. Evaluate the impact of CACC on measures of effectiveness of the simulations (Average speed, Travel Time Benefit);
5. Test the CACC simulation cases versus the baseline for statistical significance;
6. Estimate the levels of CACC technology necessary on the roadway for initial implementation.

1.3 – Scope

Traffic data was obtained for a section of Interstate highway 85 in the Auburn-Opelika area from the Alabama Department of Transportation (ALDOT). These data are then used to build a traffic microsimulation in the software CORSIM. This simulation case is defined as the baseline or initial condition case. Three parameters are varied to simulate the effects of CACC addition onto the roadway. These three parameters are CACC headway, market penetration, and traffic volume. The measures of effectiveness used for comparison of the simulations are average speed and travel time benefit. The results from simulation are then tested for significance on a statistical basis using both a t-test and multilevel ANOVA. This study gives insight into the initial parameter levels necessary for implementation of DATP on roadways.

1.4 – Outline

Chapter Two presents a detailed literature review which consists of background on CACC technology. This includes background of CACC technology and its effects on the roadway. The safety, reliability and feasibility are all detailed through past research projects. The effects of CACC technology on the drivers are also detailed through past research projects. The effects of CACC on traffic flow are investigated when all traffic can be included in the technology. Lastly, the traffic flow effects when only heavy-duty trucks are included in platoon are investigated.

Chapter Three contains the methods used to complete this project. The process used for selection of the site of simulation is given. The process of obtaining the data necessary for simulation from the simulation area is then explored. The actual modeling software implementation for both the baseline case and when the CACC technology is introduced is discussed. Lastly, the framework for statistical analysis is shown.

Chapter Four contains the results of the traffic microsimulation completed during this project. The results are shown using the measures of effectiveness of average speed and travel time benefit. The effect of the CACC parameters on each of the simulation cases is then tested for statistical significance.

Chapter Five contains the conclusions of the project along with both the recommendations and future work. The findings from chapter four are investigated and high level conclusions about DATP are discussed. The recommendations that need to be taken into account from the project are expressed. The topics that still merit further investigation in the future are shown.

Chapter 2 – Literature Review

Cooperative Adaptive Cruise Control (CACC) is an emerging technology in transportation engineering. The use of CACC could potentially double highway capacity at high market penetration through the reduction of gaps between vehicles (Van Arem et al., 2006). The impact on traffic flow will be directly related to the car-following guidelines that are set, specifically the admissible time gap between vehicles (Shladover et al., 2012). Throughout the literature on this subject there are many different techniques for setting the guidelines of following behavior. At this point there are no design standards on how to operate CACC (Arnaout et al., 2014); it is an open question as to whether such design standards are needed.

This literature review will describe the general effects of CACC technology on traffic conditions. It will discuss the reliability, safety, and feasibility of the technology. It will also discuss CACC's effect on drivers, traffic flow, and techniques for simulating the effects of the technology on roadways.

2.1 – Safety and Reliability

Driver error has less of an impact on traffic flow when CACC technology is implemented; failures from nature or vehicles still need to be taken into account (Zhang, 1996). The automated vehicle can be engineered with a large factor of safety, but a feasible cost for this is doubtful (Zhang, 1996). Thus, the CACC vehicles will need to be fail-safe, and know how to react when a non-optimal situation occurs in traffic (Zhang, 1996). Since this paper was written, the cost of technology has significantly decreased, but vehicles will still need to need operate in non-optimal situations. An automated vehicle is completing three separate roles at a time: lateral control, longitudinal control, and maneuvers for coordinating with adjacent vehicles (Zhang, 1996). Failures in any one of these systems will lead to a degraded vehicle on the road, or a potential crash. Platooning vehicles while in a platoon operate with a low delta V (ΔV) or low difference in velocities between the platooning vehicles. This means that if one of the vehicles fail and a crash occurs, it will be very low impact (Zhang, 1996). The main issue with platoon crashes is the high probability of a secondary crash event with the surrounding traffic in the area (Zhang et al., 2014). These low delta V collisions are much more likely than the high delta V collisions with individual vehicles (Zhang et al., 2014). If CACC vehicles detect an issue in the vehicle before a crash can occur, failed vehicles can stop on the roadway. This fail-safe feature can lead to issues depending on where on the roadway the vehicle stops, especially if a breakdown occurs on an entrance/exit ramp for instance (Zhang, 1996).

Riemann explored the parameter sensitivity of CACC as represented in a microscopic traffic simulation model, specifically how the ‘time to collision’ changes when these parameters are varied. There were three separate driver behaviors considered in the simulation that were all determined from a driving simulator study conducted at the Interdisciplinary Centre for Transportation Science (Riemann et al., 2012). The simulation focuses on a vehicle breaking down on the A5 motorway in Germany and the time to this vehicle becoming involved in a collision. The parameters varied in the study are the market penetration on the roadway, and the communication range of the CACC technology. The results of the simulation show when the communication range of the technology is held constant at 300 meters, the time to collision becomes statistically significant at the 80% market penetration level for CACC in comparison to the other levels of market penetration. This statistical analysis is between the market penetration levels using a multilevel ANOVA. The communication ranges of 300 meters and 500 meters are both significantly different from a baseline of 100 meters at any CACC penetration over 40% (Riemann et al., 2012).

2.2 – Human Factors

Although the drivers in a platoon have a decreased impact on operation of the vehicle, there are a different set of human factors that need to be examined. Though drivers aren't in complete control of the vehicle, the driver has the option of taking over control of the vehicle at any time they wish. There are questions about how automation can be offered while running into conflict with human capabilities in this shared control environment (Bishop, 2013). The convention for time gap between CACC vehicles in literature is from 0.5 to 1.2 seconds. A study of 400 drivers placed the mean reaction time for drivers to depress the brake pedal at 0.455 seconds (Zhang et al., 2014). When decision time is also included, it would make a driver's choice to take over the system very dangerous in typical cases at low CACC headways.

The authority transitions between the complete driver control and CACC technology still need to be reviewed in depth. An authority transition is where the driver either moves into or out of the CACC technology condition. The current car following and lane changing models do not account for these authority transitions (Varotto et al., 2014). Based on driving simulators, a situation where this issue is heightened is in dense traffic conditions. Drivers prefer to maneuver through heavy traffic conditions out of platoon to allow for them to complete high complexity movements such as lane changing (Varotto et al., 2014). The tasks that drivers will continue to complete while a vehicle is platooning will need to be clearly defined by a governing body (Bishop, 2012). The consideration of these human factors are necessary to choosing the parameters of the CACC technology that drivers will be coming into contact with on the roadway.

2.3 – Effect on Traffic Flow

2.3.1 – All Vehicles

CACC is primarily designed for driver comfort/convenience, safety, and efficiency (van Arem et al., 2006). CACC technology outperforms ACC due to less driver control efforts being necessary. The leading vehicle in a platoon dictates the action sequence, or how these vehicles will move through the roadway (Zhao et al., 2013). CACC technology operation goes through three progressions: forming, gap adjusting, and platoon steadying (Zhao et al., 2013). The convention throughout literature has been to use a time gap from 0.5 to 1.2 seconds for CACC following to keep string stable behavior. String stable behavior refers to the information moving through multiple controllers; with CACC the number of controllers and information can lead to complex non-stable behavior. The following time for manual vehicles in the literature varies from 1.25 to 1.5 seconds.

A simulation was completed using the microsimulation tool MIXIC of a four lane roadway dropping a lane to measure changes in shockwaves (Van Arem et al., 2006). The results of the simulation showed no significant difference in traffic flow when market penetration of CACC is less than 40%. CACC made lane change failures more evident; it was noted that the cooperative merging procedure needs to be investigated (Van Arem et al., 2006). Stability of the traffic improved without an increase in capacity; this could be due to the roadway in the simulation already having a traffic volume approaching capacity (Van Arem et al., 2006).

Shladover theorized that a five percent CACC market penetration would show noticeable improvement in traffic flow (Shladover, 2012). Based on this, a simulation took place focused on 6.5 km section of a single lane freeway. There are four different types of vehicles included: manual, ACC, ‘here I am’ (non-ACC vehicles that broadcast location and speed), and CACC. The study varied the penetration levels for both ACC, and CACC through multiple trial simulations. Results showed ACC to have little impact on increasing the baseline (manual) lane capacity which was 2200 vehicles per hour (Shladover, 2012). The simulation shows at 100% penetration of CACC the lane capacity can increase up to 4000 veh/h (Shladover et al., 2012). If vehicles that do not have CACC technology are equipped with ‘Here I am’ (HIA) they can be the leading car in a platoon (Shaldover et al., 2012). At a 20% market penetration of CACC, HIA can increase the capacity of a roadway 7% (Shladover et al., 2012). The impact of HIA is heightened at greater CACC market penetrations; at 60% CACC, the capacity increases by 15%.

Another simulation framework focused on traffic flow stability (Schakel et al., 2010). The simulation is completed on a 4.0 kilometer section of a single lane road. The traffic begins moving at 90 kilometers per hour, for 80 seconds, then decelerating to 36 km/h, at this point they then accelerate back to 90 km/h. This study simulated a shockwave in the traffic flow. This simulation looked at CACC penetration levels of 0, 50, and 100 percent. The results showed CACC will increase the initial deceleration of a shockwave, this will shorten the duration and increase the range (Schakel et al., 2010). The shockwave speed could pose issue to human drivers on the roadway (Schakel et al., 2010).

Zhao focused on a 4 km stretch of a two lane freeway. This simulation focused on how platoon size will affect capacity. It showed that a platoon size ranging from 2 to 10 vehicles did not have much impact on roadway capacity (Zhao et al., 2013). An increase in market penetration has greater impact on roadway capacity as compared to platoon size. At 100% market penetration the capacity did not increase with an increase in platoon size. Platoon size increase will lead to difficulty for vehicles trying to merge and weave to exit if large platoons are on the roadway.

Arnaout looked at initial deployment strategies for CACC technologies. Prior research tends to indicate CACC technology is not beneficial under 40% penetration. A 6km 4-lane freeway was modeled in the F.A.S.T. simulator. F.A.S.T. is a simulator developed by Arnaout focusing on freeway scenarios. The simulation took place both including and without a ramp. The three cases of simulation are no CACC, 20% CACC in a HOV lane, and 20% CACC in mixed traffic. When a ramp was included, the flow rate of traffic increased in both CACC instances (Arnaout & Bowling, 2014). Overall travel time on the roadway is the smallest in the scenario with an HOV lane, though as the flow of traffic increases results becomes similar in all cases (Arnaout & Bowling, 2014). The highest average speed comes from the mixed traffic CACC, while the HOV case had steadier traffic flow (Arnaout & Bowling, 2014). The results when a ramp is not included are as follows. The HOV case will increase the flow rate and average speed even at low penetration rates and the mixed case is not significantly different from the baseline (Arnaout & Bowling, 2014).

2.3.2 – Truck Platooning

The greatest benefits from platooning will be in the monotonous environment of the US interstate system (Devitt et al., 2013). Platooning savings accounting for labor savings, fuel efficiency, productivity gains, and accident savings are estimated at $168 billion dollars annually (Devitt et al., 2013). The truck industry is more homogeneous in specifications and performance parameters than the car industry; this can lead to efficient regulation of the CACC industry

(Ploeg et al., 2011). Truck drivers can coordinate behavior at exits to let vehicles cross a platoon and exit (Ploeg et al., 2011). This situation where platoons of heavy-duty trucks block vehicles from exiting the roadway is one of the most complex problems with DATP. This is the main reason that platoon length will be restricted when this technology is initially implemented. Aftermarket and service channels for trucks can enable a swift introduction of CACC (Ploeg et al., 2011). Trucks undergo a very stringent certification process that would allow the government mandate the number of trucks on the roadway with this technology.

It has been shown that string stable behavior is possible with heavy duty trucks with sufficiently large headway times (Nieuwenhuijze et al., 2012). String stable behavior means that any errors or disturbances from any vehicle in the stream do not propagate upstream. When not string stable the capacity of a roadway is negatively affected. String stable behavior is enhanced by having the lighter truck following in the platoon (Nieuwenhuijze et al., 2012). This is a variable that companies could use to when scheduling potential platooning partners.

Trucks are electronically limited to a top speed that naturally clusters them on highways; drivers already have a cooperative approach (Ploeg et al., 2011). Platoon trip planning would need to focus on the efficiency of the trucks on the roadway, while still maintaining the maximum amount of fuel savings. Coordination between multiple companies may help to find all trucks a platooning partner. This would also make the coordination of fuel savings more complex, as platoon position is extremely important to the fuel savings amount.

2.4 – Summary

This chapter explored the existing research on the subject of cooperative adaptive cruise control. There are many variables in the implementation of CACC onto a roadway including the safety and reliability of the CACC system, the effect this technology will have on both the drivers of the vehicles and on traffic flow of the roadways.

The effects on traffic flow were found to focus on the use of microsimulation in order to find the potential benefit of the technology. In comparison to passenger vehicles in the implementation of CACC technology, there is little research focusing specifically on heavy duty trucks in the implementation of this technology. The studies that have been published focus on how this implementation would occur and not on actual microsimulation of this scenario. With the length of heavy duty trucks, the length of these platoons will need to be smaller to allow for vehicles that need to merge and weave on these roadways. The homogeneity, speed, and regulation of heavy duty trucks on freeways will allow for swift introduction of DATP onto roadways.

Chapter 3 – Methodology

This chapter begins by describing the process of selecting a site for the traffic simulation to take place. The data collection process that needs to take place for simulation is then explained. The framework for building the traffic simulation in the modeling software CORSIM is shown. This includes both the initial building of the simulation network, in addition to the model necessary for the driver assisted truck platooning (DATP) technology. The outputs of the model or measures of effectiveness are then introduced. Hypothesis testing in the form of a t-test and a multilevel ANOVA are used to show which traffic simulation cases and DATP parameters are statistically significant.

3.1 – Site Selection

The introduction of DATP technology will affect roadways in different ways. The type of roadway chosen as the simulation environment will have a strong effect on the outputs. By controlling access onto a roadway, the efficiency of the roadway is increased. A freeway was chosen to be the simulation site as this is the type of roadway with the greatest control of access. Additionally, freeways are the environment where long distance freight movements occur, and traffic is not affected by traffic signals. Interstate 85 in Alabama was chosen for the simulation as it was considered to be a representative segment of rural freeway and small urban area interaction, the proximity of the site to Auburn, and availability of traffic data. Traffic data was obtained from the Alabama Department of Transportation (ALDOT). The simulation looks for an improvement in efficiency on the roadway, thus traffic flow needed to be approaching capacity, but traffic still needs to be moving throughout the segment in the baseline condition for potential benefits to be realized. This kept the choice of segment away from highly urban areas, such as Montgomery, where traffic volume approaches capacity during the peak hour. This also keeps the choice away from highly rural areas on I-85, where the peak hour volume does not approach the capacity of the roadway. This leaves the rural sections of the roadway that move through a small city and will see significant difference in traffic flow during the peak hour of the day compared to the average hour of traffic. After studying the possible sections of the interstate possible, a segment on I-85 through the Auburn-Opelika area was chosen. The section was just north of Auburn University and is shown in Figure 3.1. The segment is a 5.3 mile section of I-85 northbound from just south of Exit 58 to just north of Exit 62. This allows the model to include three different interchanges. Having three exits in the model gives added complexity to the model as there are many decisions for the roadway users to make. These interchanges give the roadway users in the dominant direction potential conflict points while navigating the simulation area. This increases the complexity of the simulation and approaches real world conditions.

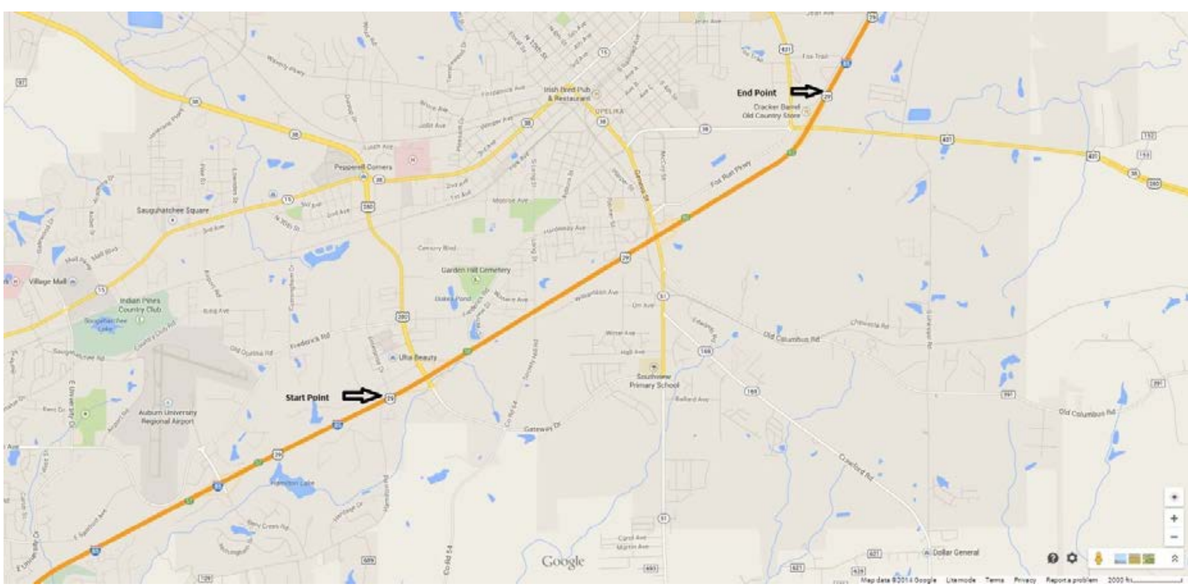

Figure 3.1: Map of Simulation Area

3.2 – Data Collection

Using a section of I-85 allows for the data needed for the traffic simulation to be obtained from the ALDOT Traffic Data website. Examples of the data from the traffic data website can be seen in Figures 3.2 and 3.3. ALDOT provides traffic data values between the interchanges on the roadway and for each of the on/off ramps. In addition to traffic counts, the website also presents other values that are necessary for examination of the section of roadway. The K-factor or the proportion of daily traffic occurring during the peak hour, D-factor or directional distribution of traffic are both values that will be used in the formulation of the peak hour traffic volume. The data dictionary of the ALDOT traffic count website including the TDHV and TADT is shown in Table 3.1.

Figure 3.2: ALDOT Traffic Count Data at Exit 60 (ALDOT, 2014)

Term	Definition
AADT	The annual average daily traffic count for the segment represented (Total of all vehicles counted in a year divided by 365 days). AADT is calculated annually for all highway segments.
AADT Year	The calendar year for which AADT was calculated.
K	Design Hour Volume defined as the 30th highest annual hourly traffic volume expressed as a percentage of AADT.
D	The percentage of the design hour value flowing in the peak direction.
TDHV	Commercial vehicles in the design hour expressed as a percentage of the DHV.
TADT	Commercial vehicles, composed of trucks of all types, expressed as a percentage of AADT.
Heavy	Heavy trucks; Trucks with 3 or axles.
Functional Class	The classification of the segment of road, as defined by FHWA, which is broken down between rural and urban areas. The functional classification system is based on the grouping of streets and highways into classes, or systems, according to the character of the service they are intended to provide.

Table 3.1: ALDOT Traffic Count website term definitions (ALDOT, 2014)

The values from the ALDOT website are used to find the peak hour volume (PHV) on the roadway. The volumes are initially given as an Average Annual Daily Traffic (AADT); this AADT is then converted into a design or peak hour count using ‘K’. This is shown in equation (1). The K factors on this section of I-85 range from 10 to 11 percent. This value is then multiplied by the D-factor to find the directional design hourly volume or the peak hour volume of traffic in the dominant direction of the traffic flow. This is shown in equation (2). These peak hour volumes are what will be used as inputs into the traffic simulation, they are summarized for the mainline traffic in Table 3.2. At this point the traffic data needed to build the simulation framework are ready for use in the traffic simulation software.

$$DHV = (AADT)\ (K) \qquad (1)$$

$$DDHV = (DHV)\ (D) \qquad (2)$$

Location	AADT	K-Factor	Peak Hour Volume	D-Factor	Northbound Peak Hour Volume
Between 57 and 58	39900	0.11	4389	0.65	2853
Exit 58 Off Ramp	4240	0.10	424	1	424
Exit 58 On Ramp	7790	0.10	779	1	779
Between 58 and 60	45360	0.11	4989.6	0.65	3243
Exit 60 Off Ramp	2300	0.10	230	1	230
Exit 60 On Ramp	2380	0.10	238	1	238
Between 60 and 62	45490	0.11	5003.9	0.65	3253
Exit 62 Off Ramp	9860	0.10	986	1	986
Exit 62 On Ramp	2700	0.10	270	1	270

Table 3.2: Baseline Traffic Volume Information

3.3 – Modeling Software

Microscopic traffic simulation allows for a theoretical traffic situation to be modeled without the cost of the actual situation being implemented on the roadway. The use of microscopic traffic simulation has become more prevalent in transportation research as the cost of computing has lessened over the years. One of the most prevalent microscopic simulators is CORSIM, which was created by the McTrans Center at the University of Florida in 1998. Program development has been funded throughout the years by the Federal Highway Administration (FHWA). CORSIM is a text-based simulator. Each roadway built in the simulator corresponds to a ‘Record Type’ or line of code that explains characteristics. CORSIM is a combination of NETSIM, a network simulator, and FRESIM, a freeway simulator. The framework built in CORSIM to model the baseline traffic segment of I-85 can now be investigated.

3.3.1 – Baseline Model Framework

The traffic simulation being built is based on the peak hour of traffic flow. The simulation focuses on only one direction of traffic. This is because on a freeway there is no interaction between the directional traffic streams. The network that is built is based on the northbound direction of traffic. The initial network model is built in TSIS 6, the program that houses CORSIM and where each model is run. The highway segment is constructed using freeway nodes, and the on and off ramps are built using surface nodes. Figure 3.4 shows the network at exit 60. Figures 3.5 and 3.6 show the details of the on and off ramps that correspond to exit 60. In Figure 3.5 the relative turn volumes were manipulated. This shows that 91% of the vehicles moving through this node are through traffic and 9% is exiting at exit 60. In Figure 3.6 both the volume and percent trucks were manipulated. The volume is the number of vehicles that enter the roadway at exit 60, and the percent trucks is the heavy-duty percentage of the volume.

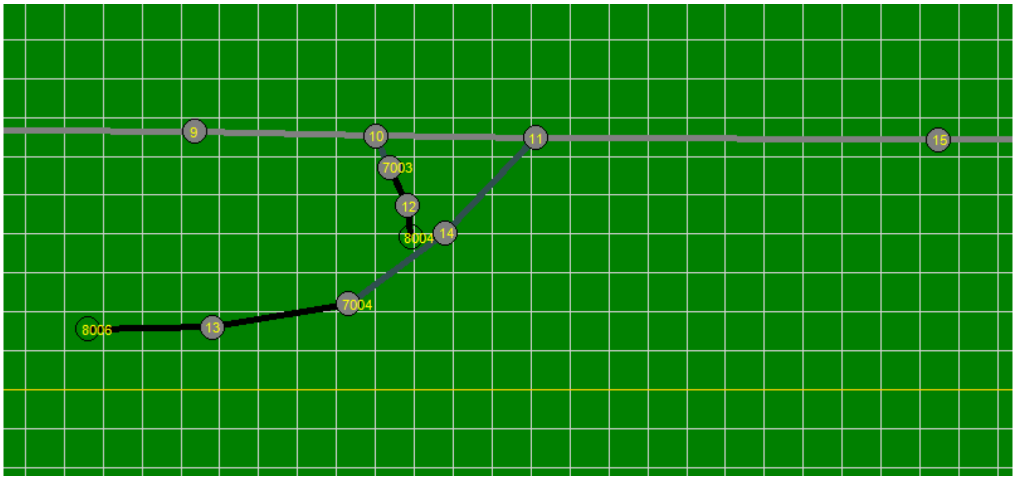

Figure 3.3: CORSIM Network at Exit 60 of I-85

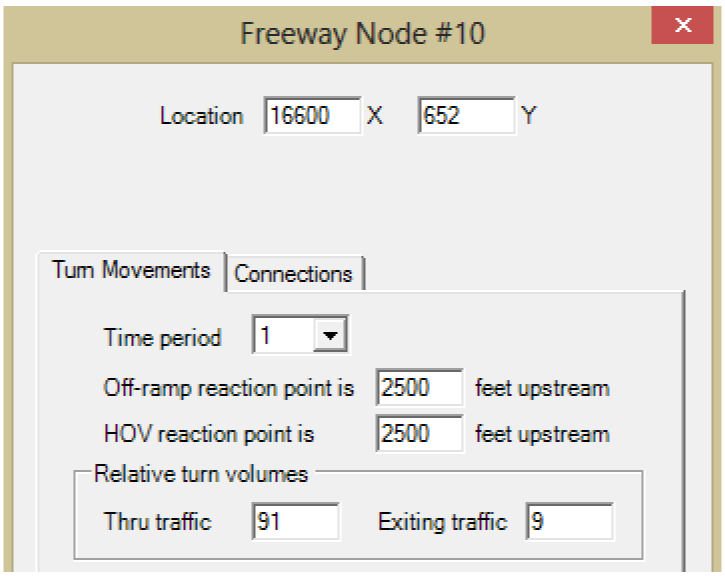

Figure 3.4: CORSIM Node #10 or Exit 60 Off Ramp

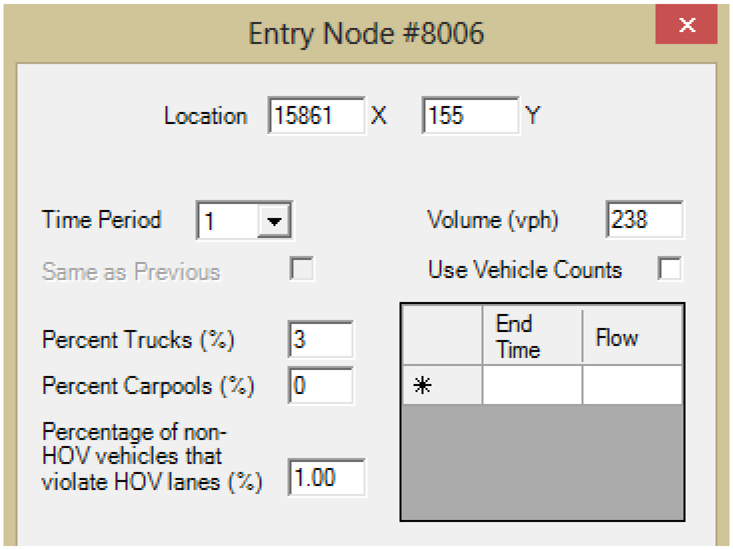

Figure 3.5: CORSIM Node #8006 or Exit 60 On Ramp

The full roadway network is built following the same procedure as shown for Exit 60. After the full roadway network is built the baseline model is then complete and the DATP or advanced technology case can now be built for simulation.

3.3.2 – CACC Model Framework

In the baseline simulation all of the vehicles on the roadway have the same car following behavior. The headway of passenger vehicles without any advanced technology is a distribution centered on a value of 1.50 seconds. The car-following model is based on the premise that drivers desire to follow the car in front of them at a given sensitivity factor. The factor differs from driver to driver and CORSIM uses ten different values for the sensitivity factor (McTrans, 2010). This is manipulated in the record type 68.This is the normal distribution of drivers in traffic and the random characteristics of individual's car following maneuvers follow the University of Pittsburgh (Pitt) car following model. This model incorporates the distance headway and speed differential between the lead and follower vehicles. The Pitt car following model allows setting a minimum distance between lead and following vehicles regardless of speed (Rakha et al., 2002). This framework is shown used in the baseline model, but when DATP vehicles come into the model it is necessary to augment the following parameters for these trucks on the roadway. The software allows for the modeling of advanced technology vehicles with their own headway distribution by flagging them when they enter the roadway. The flagged vehicles' headways are set instead of their car-following sensitivity factor. This means the percentage of advanced technology vehicles or CACC vehicles car-following sensitivity factor is now their CACC headway value.

The percentage of trucks that use the advanced technology are set when the percentage of trucks in the simulation are set giving the market penetration of each case. This is what allows for varying levels of market penetration. All of the trucks in the simulation are set to a trailer length of 53 feet. Platoons enabled by equipped vehicles were limited to two-vehicle platoons, these platoons enter the roadway together and travel the full segment. With both the framework for simulation of the baseline and DATP cases complete the parameters that will be varied in simulation can now be discussed.

3.4 – CACC Parameters

Initially there were eight characteristics that were considered to be varied in the process of modeling CACC technology. Five of these characteristics were discarded from the model cases, each of these parameters will now be investigated in depth. The platoon size is limited because of the length of the heavy-duty trucks that enter platoons. In the original simulation framework platoons lengths of both two and three trucks were considered. Three truck platoons were eliminated as in mixed traffic these large platoons will inhibit non-platoon vehicles from merging and weaving throughout the lanes. These large platoons can block vehicles from entering or exiting the roadway when they are close to interchanges. The truck percentage on the roadway is limited to what is seen in the peak hour of traffic of the day. Thought was given to using other truck percentages including the percentage of trucks in the average hour of traffic and the percentage of trucks in the peak truck traffic hour. The greatest benefit of DATP technology is assumed to be found when the traffic on the roadway is at its highest, thus the simulation focuses on the peak hour of traffic. The communication range of the CACC technology was briefly investigated. This parameter is largely independent of the traffic flow, and would not have added substantial information to our results. The lane use of the technology was considered. The platooning could be restricted to certain lanes on the roadway or allowed in all lanes (mixed traffic). The section of I-85 used for simulation is two lanes and did not lend itself to having lane restrictions. Lane restriction is normally done on roadways of three or more lanes. The last parameter investigated was having vehicles on the roadway that with only adaptive cruise control (ACC) capability. This would allow those vehicles to run at smaller headways than normal traffic, but not with the efficiency of the CACC vehicles. There is already extensive literature on the ACC technology and the added benefit from this simulation case was not seen to be beneficial to the investigation.

There were three characteristics varied in the simulation. These were DATP headway, market penetration, and peak hour traffic volume. The non-advanced technology vehicles headway are on a distribution that is centered at a value of 1.50 seconds. The advent of DATP technology has two main benefits, these are eliminating the variability of headway on the roadway, and lowering the headway value. Thus instead of a centered distribution the DATP headway values will be a single value. There are four values that are used in the model: 1.25s, 1.00s, 0.75s, and 0.50s. These values are chosen to show a likely initial implementation value for the technology, down to a theoretical value that may be seen in the future. In addition to the headway used in DATP, the market penetration of the technology also needs to be taken into account. There are five values used for this parameter: 20%, 40%, 60%, 80%, and 100%. Varying market penetration will allow those that regulate this technology to identify the amount of penetration necessary to introduce DATP into all traffic streams. As an example of how market penetration level affects the platooning of heavy trucks in a simulation, if a simulation run at 20% market penetration included 100 heavy trucks, 20 of them would have DATP capability. This results in 10 two-truck platoons with the other 80 trucks not operating in platoon. None of the passenger vehicles in the simulation have CACC capability. The traffic volumes are the third parameter in the simulation: Baseline peak hour volume (PHV), 115% PHV, and 130% PHV. Traffic volume increases are modeled to address traffic growth over time as well as scenarios in which volumes approach capacity. The traffic volume increases are capped at 130% due to the capacity of the roadway. Initially, volume increases up to 150% were included, and the roadway could not adequately compensate for this throughput.

The three parameters of headway, market penetration, and traffic volume were varied in order to examine the effect of each on the other two parameters. Including the baseline cases of all three traffic volumes, there are sixty-three simulation cases. Each of these sixty-three models is run three times with varying random number seeds and averaged.

- Traffic Volume: Current Conditions, 115% of Current Conditions, 130% of Current Conditions
- CACC Headway: 1.25s, 1.00s, 0.75s, 0.50s
- Market Penetration: 20%, 40%, 60%, 80%, 100%

3.5 – Statistical Analysis

After all of the simulation cases are run the results are analyzed for statistical significance. This process is done using both a student's t-test and a multilevel ANOVA. The student's t-test focuses on each of the simulation scenarios. An example of this is the case of current traffic volume, 20% market penetration, and 1.25 second headway. For each case the mean and standard deviation are obtained from the three runs used for each of the scenarios. These results can then be tested using the student's t-test to find the one-sample t-test value and the corresponding p-value. The null hypothesis of testing is that the mean of the three iterations of each simulation case is not significantly different from the corresponding baseline traffic volume case. The alternative hypothesis is that the mean of the three iterations of simulation case tested is significantly different from the corresponding baseline traffic volume. The two significance levels used for testing are $\alpha=0.05$ and $\alpha=0.01$. Two significance levels are used show the effect of these parameters with greater effect. Cases that are significant at either of the significance levels are shown in the results section. This analysis of the student's t-test is done using Microsoft Excel.

The multilevel ANOVA focuses on each of the levels of the market penetration and headway parameters. The multilevel analysis of variance (ANOVA) is a multiple comparison, or comparison of means across the same group, shows if there is a significant difference between the levels of a factor, keeping other factors constant. The variance of each of these parameters is the focus of the ANOVA testing. The null hypothesis of this testing is that the means of travel time benefit are equal between the parameter levels. The alternative hypothesis is then that at least one means of travel time benefit at a parameter level is different from the others. At this point if the ANOVA shows that the alternative hypothesis is true a post hoc test is used to find which of the parameters is significantly different from the others. Tukey's honest significant difference (HSD) is used for this testing. Tukey's HSD is a statistical test that compares all possible pairs of means for significance. This test is chosen because all the comparisons are pairwise. The procedure calculates the studentized range statistic using the two means and the standard error of the data. This procedure is similar to student's t-test which is also used in this statistical investigation (NIST, 2012). The difference of the means of the two parameter levels is divided by the standard error of the data. This equation for the studentized range is shown below. The means are shown as μ_1 and μ_2, and SE is the standard error of the data (NIST, 2012). The significance level used for the ANOVA testing is $\alpha=0.05$. The analysis of both the multilevel ANOVA and post hoc Tukey's comparison are completed using IBM SPSS.

$$Q = (\mu_1 - \mu_2) / SE \qquad (3)$$

3.6 – Summary

This chapter presented the selection of the site for traffic modeling and how the data obtained from ALDOT was used to have inputs for the traffic simulation. The details of how these inputs are used to create the baseline simulation are then discussed. The integration of DATP technology into the traffic model is shown, along with the parameters that are varied in the modeling process. Lastly, the process of statistical analysis of traffic simulation results are discussed. The results of the traffic simulation built using the methods from this chapter are presented in Chapter Four: Results.

Chapter 4 – Results

This chapter reveals the results of the methodology which was described in Chapter Three. Chapter Four summarizes the results of traffic microsimulation accomplished in CORSIM. The results of simulation are analyzed using travel time benefit (derived from delay) and average speed as the measures of effectiveness. There are a total of sixty three simulation cases; each case is comprised of three trials that are analyzed. The parameters used are broken down into the three traffic volumes, four headways, and five market penetrations. These three parameters are varied giving sixty cases along with the three baseline simulations. The three baseline simulations correspond to each of the traffic volumes used which are the current peak hour volume, 115% PHV, and 130% PHV. The statistical significance of these results will be analyzed using a student's t-test to evaluate differences in travel time between each simulation case and its applicable baseline case. Statistical significance will also be analyzed using a multilevel ANOVA to evaluate if there are significant differences between the multiple levels of a parameter. Tukey's comparison will then be used to analyze which of these parameter cases is significantly different from the others. The statistical results will give added information into what combination of parameters will give beneficial effects to traffic flow.

4.1 – Traffic Volume and Baseline Results

Figure 4.1, comparison of baseline delay at the three traffic volumes, compares each of the baseline traffic simulations using the measure of effectiveness of delay. Delay (given in seconds) is the amount of time increase in comparison to free flow conditions for a vehicle to travel through the simulation environment. This value is found for each of the vehicles in the simulation and aggregated into the delay value for the simulation case. As traffic volume is increased on a roadway the amount of congestion will also increase, and thus the potential DATP impact would also increase. This is the case for the two of the forecasted traffic volumes used in this simulation. The current traffic volume will not see the same amount of benefit as either of the forecasted values because it initially has less delay. The added benefit from initially having more delay on the roadway exists until traffic volume approaches capacity. At capacity, DATP technology will not affect the amount of delay, there is so little movement that the possible benefits of DATP are dissipated. The DATP technology will allow for the congestion to dissipate quickly after an adverse traffic event.

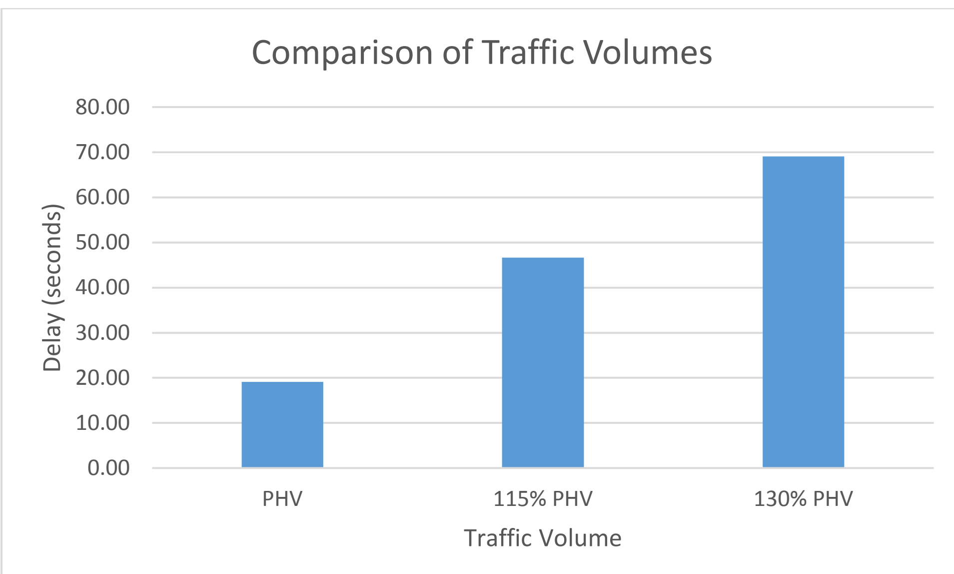

Figure 4.1: Comparison of Baseline Delay at Current, 115%, and 130% Traffic Volumes

4.2 – Effect of Headway on Average Speed and Travel Time Benefit

The effect of the differences in average speed and travel delay due to the four levels of headway are analyzed when holding all other factors constant. As an example, Figures 4.2 and

4.3 show the average speed and travel delay for the vehicles on the roadway at the current peak hour volume and 100% DATP market penetration. The travel delay results correspond to the additional time (in seconds) needed for each vehicle to complete its movement through the roadway as compared to free flow conditions. The travel delay results shown are the aggregate of all the vehicles on the roadway. The full results from all simulation cases are shown in the tables at the end of the results section.

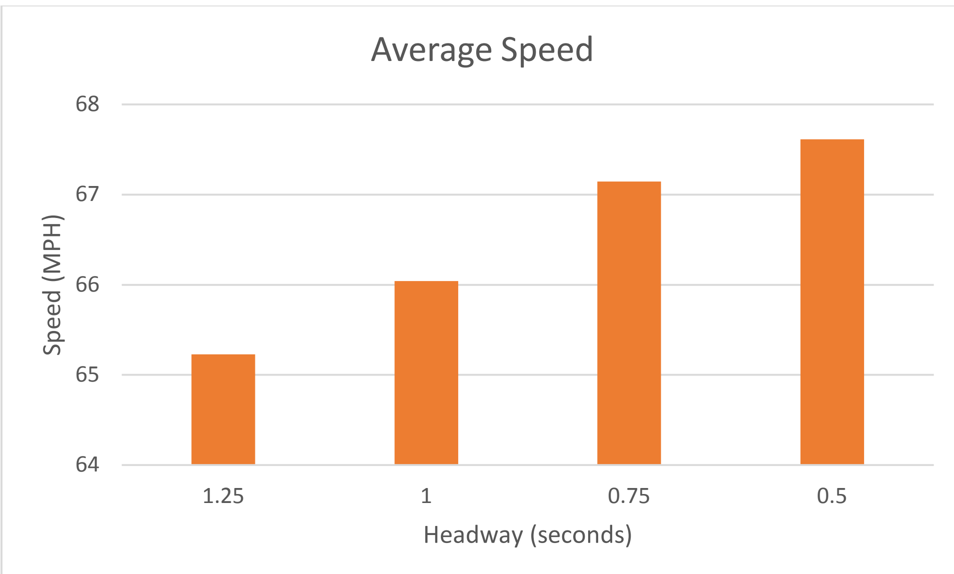

Figure 4.2: Average Speed at Current Traffic Volume and 100% Market Penetration

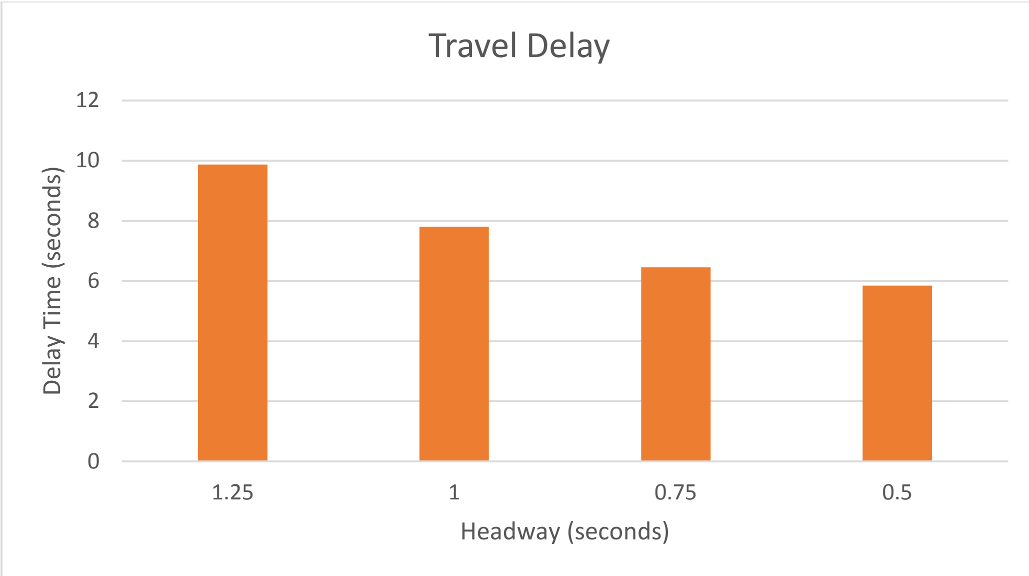

Figure 4.3: Travel Delay at Current Traffic Volume and 100% Market Penetration

The non-CACC vehicles on the roadway are moving on a headway distribution centered at a value of 1.5 seconds. This distribution uses the record type 68 in CORSIM to set the car following sensitivity of the ten driver types. The record type is based on the belief drivers like to follow other vehicles at a set headway value which varies from driver to driver (McTrans Center, 2010). The average speed examined above shows how closing the gaps between the platoons allow for more efficient movement through the section of roadway. The increase in average speed is directly related to the decrease in delay time, this relationship is apparent in Figures 4.2 and 4.3.

4.3 – Effect of Market Penetration on Average Speed and Travel Time Benefit

The market penetration was also varied using five different values. The results of this examination are found in Figures 4.4, 4.5, and 4.6. The measure of effectiveness in these figures is the average speed. Each figure includes the average speed at all the headways which were included in simulation. The relationship between these two parameters must be examined before DATP technology can be implemented on roadways. These figures show that market penetration's effect on traffic efficiency is largely dependent on the chosen headway of vehicles. This relationship is shown in increase in average speed at a headway as the market penetration increases. At the 1.25 second headway there is little increase as the penetration is increased. At the 0.50 second headway the increase average speed through increasing the market penetration is the highest. This shows that the effect of increasing the market penetration value will have a more drastic effect on the average speed. This trend is the same regardless of the traffic volume investigated.

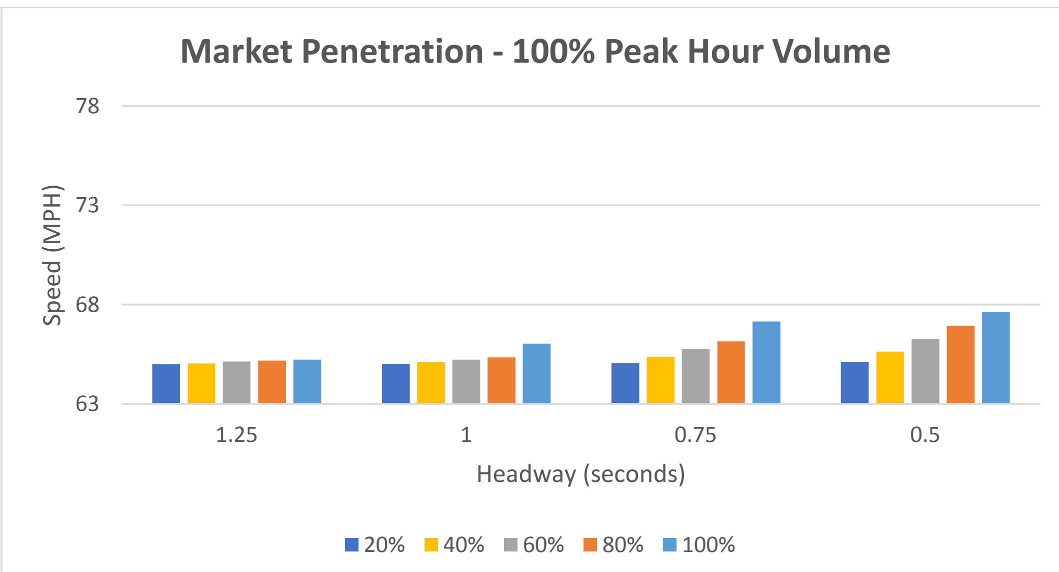

Figure 4.4: Average Speed at Current Traffic Volume at all Market Penetration Values

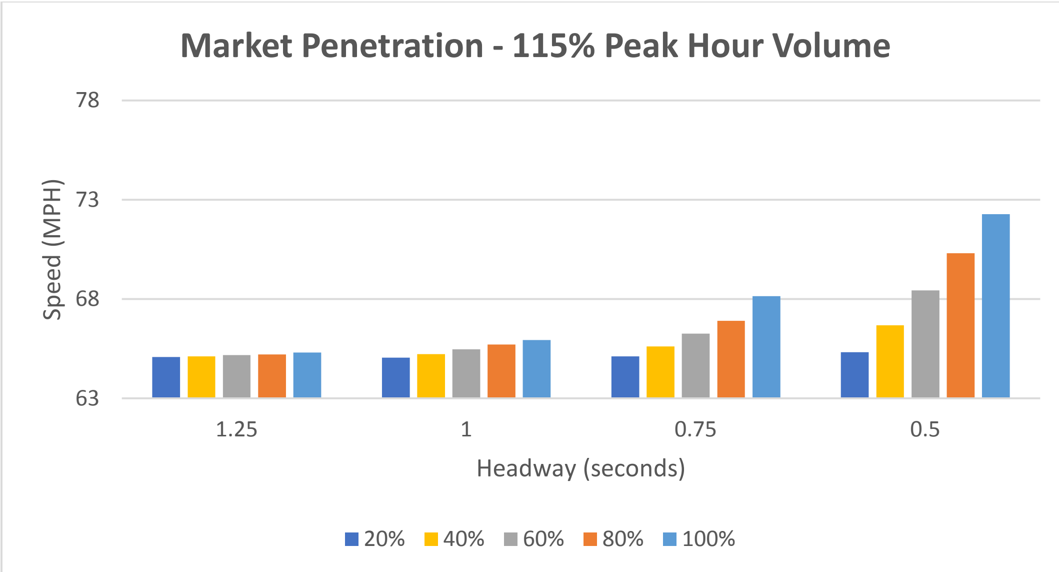

Figure 4.5: Average Speed at 115% Current Traffic Volume at all Market Penetration Values

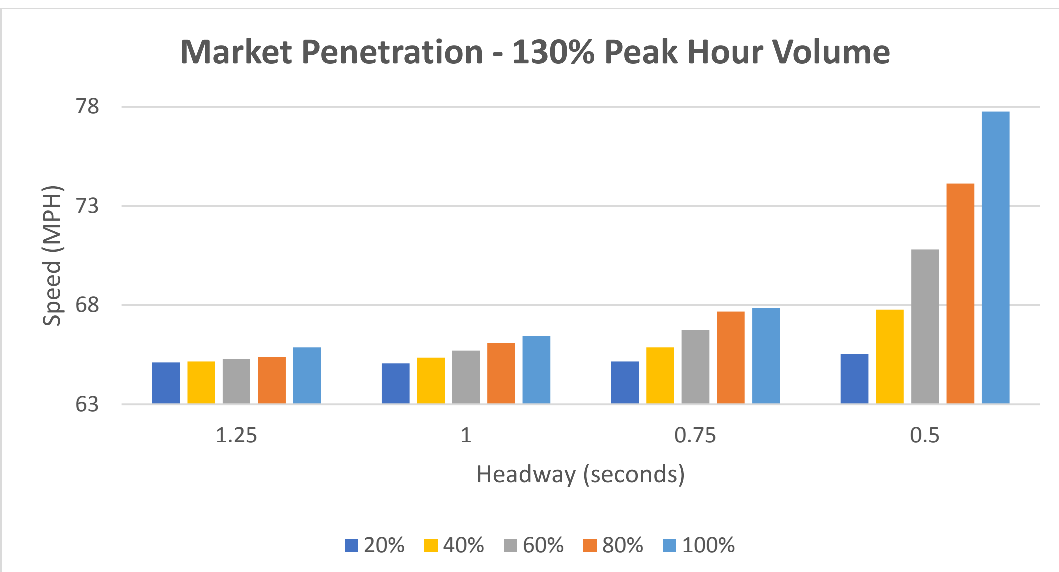

Figure 4.6: Average Speed at 130% Current Traffic Volume at all Market Penetration Values

4.4 – Traffic Simulation Results

Table 4.1 shows the results of the baseline simulation cases. These results correspond to the total 5.3-mile segment which was modeled with no market penetration of DATP. The measures of effectiveness are shown for these baseline cases at each of the three values of traffic volume. These baseline values are necessary for both determining the travel time benefit for each of the simulation cases and use in the statistical investigation.

Baseline Model Results		
Traffic Volume	Travel Delay (sec)	Average Speed (mi/h)
PHV	19.11	65.02
115% PHV	46.68	65.11
130% PHV	69.08	65.07

Table 4.1: Baseline Model Results

Tables 4.2-4.7 show the summary of results for all the possible combinations of the DATP parameters. Tables 4.2-4.4 focus on the travel time benefit shown in the simulation cases. These are calculated by subtracting each case's travel delay from the corresponding baseline traffic volume case. The result is the travel time reduction benefit for each of the simulation cases. These results show that as the headway decreases at a market penetration the amount of benefit to the system will increase. This effect is amplified with an increase in the traffic volume. This same effect is found for market penetration when the headway is held constant. These results are similar to what was expected when compared to the literature on the subject. Tables 4.5-4.7 show the average speed results for each of the simulation cases. The trends discussed for the travel time benefit match what is shown in the average speed results. This is expected as the travel time benefit and average speed results are highly correlated. It is necessary for these results to point out that the average speed results may be counterintuitive due to each traffic volume starting with the same average speed. In practice, on the same section of roadway when the volume is increased the average speed will decrease. Thus, this leads to what may be seen as overstatement of the effect of the DATP technology in the cases with higher traffic volume.

100% Peak Hour Volume - Travel Time Benefit					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	0.35	4.10	5.98	7.85	9.24
1	3.49	5.97	8.17	9.74	11.30
0.75	6.21	8.79	10.08	10.66	12.66
0.5	7.69	9.75	10.92	12.09	13.26

Table 4.2: Travel Time Benefit Results at the Current Traffic Volume

115% Peak Hour Volume - Travel Time Benefit					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	5.13	13.44	17.60	21.75	25.91
1	22.86	27.63	30.01	32.39	34.77
0.75	28.08	31.80	33.66	35.52	37.38
0.5	31.07	34.19	35.75	37.31	38.87

Table 4.3: Travel Time Benefit Results at 115% Current Traffic Volume

130% Peak Hour Volume - Travel Time Benefit					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	1.53	15.04	19.80	30.63	35.31
1	35.47	40.39	45.56	47.91	52.28
0.75	43.58	45.63	51.23	55.67	56.06
0.5	50.15	53.13	54.98	57.10	58.84

Table 4.4: Travel Time Benefit Results at 130% Current Traffic Volume

Tables 4.5-4.7 show the average speed results for each of the simulation cases.

100% Peak Hour Volume - Average Speed in MPH					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	65.01	65.04	65.14	65.19	65.23
1	65.02	65.11	65.23	65.34	66.04
0.75	65.08	65.38	65.76	66.15	67.14
0.5	65.13	65.63	66.28	66.94	67.61

Table 4.5: Average Speed Results at the Current Traffic Volume

115% Peak Hour Volume - Average Speed in MPH					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	65.09	65.11	65.19	65.22	65.31
1	65.05	65.23	65.47	65.71	65.95
0.75	65.12	65.62	66.26	66.90	68.15
0.5	65.33	66.68	68.45	70.31	72.28

Table 4.6: Average Speed Results at 115% Current Traffic Volume

130% Peak Hour Volume - Average Speed in MPH					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	65.12	65.17	65.28	65.40	65.87
1	65.07	65.36	65.72	66.09	66.46
0.75	65.17	65.87	66.77	67.68	67.86
0.5	65.54	67.78	70.81	74.12	77.76

Table 4.7: Average Speed Results at 130% Current Traffic Volume

4.5 – Statistical Testing

This simulation included 3 baseline simulation cases and 60 cases of the possible combinations of DATP parameters. After obtaining these results it is necessary to find which DATP cases are significantly different from the baseline. Each of the cases is statistically tested using a t-test to obtain the p-value. The mean travel time benefit value of 3 simulations for each case is tested to see if it statistically significantly different from the mean of the baseline case at the corresponding traffic volume. The statistical investigation of results is focused on the travel time benefit results. Doing this testing on both of the measures of effectiveness would be redundant. The full t-test results will be in the attached appendix. Tables 4.8-4.10 show the travel time benefit results for the three traffic volumes cases with the results of the student's t-test. At the current peak hour volume the lowest market penetrations, 20% and 40%, are only significant at low headway values. As the market penetration increases more of the headway values become significant. For both the 115% and 130% peak hour volume the increase in travel time benefit has such an impact on these results that only the case with 20% market penetration and 1.25 second headway is not at all significant.

100% Peak Hour Volume - Travel Time Benefit					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	0.35	4.10	5.98	7.85*	9.24*
1	3.49	5.97	8.17*	9.74**	11.3**
0.75	6.21	8.79*	10.08*	10.66*	12.66**
0.5	7.69*	9.75**	10.92**	12.09*	13.26**

Table 4.8: Travel Time Benefit at the Current Traffic Volume with Statistical Results
(* denotes significance at the α=0.05 level and ** denotes significance at the α=0.01 level)

115% Peak Hour Volume - Travel Time Benefit					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	5.13	13.44**	17.60**	21.75**	25.91**
1	22.86**	27.63**	30.01**	32.39**	34.77**
0.75	28.08**	31.80**	33.66**	35.52**	37.38**
0.5	31.07**	34.19**	35.75**	37.31**	38.87**

Table 4.9: Travel Time Benefit Results at 115% Current Traffic Volume with Statistical Results
(* denotes significance at the α=0.05 level and ** denotes significance at the α=0.01 level)

130% Peak Hour Volume - Travel Time Benefit					
	Market Penetration (%)				
Headway (s)	20%	40%	60%	80%	100%
1.25	1.53	15.04*	19.80*	30.63**	35.31**
1	35.47**	40.39**	45.56**	47.91**	52.28**
0.75	43.58**	45.63**	51.23**	55.67**	56.06**
0.5	50.15**	53.13**	54.98**	57.10**	58.84**

Table 4.10: Travel Time Benefit Results at 130% Current Traffic Volume with Statistical Results
(* denotes significance at the α=0.05 level and ** denotes significance at the α=0.01 level)

In addition to the t-test used to find statistical significance of differences between each individual case and the baseline case, each of the parameters is also investigated. This is done using a multilevel ANOVA. Multilevel ANOVA is a multiple comparison test that shows if there is a significant difference between the levels of a parameter. The results of ANOVA are shown in Figures 4.7-4.9. These results show that at each of the three levels of traffic volume the ANOVA results show that there is significant difference between the levels of each of these parameters. In addition to the parameters, there is another term which is the Market Penetration * Headway term. This interaction term corresponds to the interaction of the two parameters of market penetration and headway and is added to observe the effect of the these parameters on each other. This term is not significant for the 100% and 115% traffic volumes. This means that these two terms are independent for one another and changes to either of them may lead to significant results. This term is significant for the 130% traffic volume. The two parameters are not independent from one another and changes to either of the parameters can lead to significant changes in the model.

Source	Type III Sum of Squares	df	Mean Square	F
Corrected Model	622.27	19	32.75	6.22*
Intercept	6864.27	1	6864.27	1303.39*
Market Penetration	367.14	4	91.78	17.43*
Headway	239.49	3	79.83	15.16*
MP * Headway	15.64	12	1.3	0.25

Table 4.11: Multilevel ANOVA F-test Results at the Current Traffic Volume
(* denotes significance at the α=0.05 level)

Source	Type III Sum of Squares	df	Mean Square	F
Corrected Model	4424.43	19	232.87	14.47*
Intercept	19276.19	1	19276.19	1197.73*
Market Penetration	3144.11	3	1048.04	65.12*
Headway	1100.73	4	275.18	17.09*
MP * Headway	179.59	12	14.97	0.93

Table 4.12: Multilevel ANOVA F-test Results at 115% Current Traffic Volume
(* denotes significance at the α=0.05 level)

Source	Type III Sum of Squares	df	Mean Square	F
Corrected Model	13740.52	19	723.19	61.76*
Intercept	42360.02	1	42360.02	3617.49*
Market Penetration	10562.93	3	3520.98	300.69*
Headway	2477.49	4	619.37	52.89*
MP * Headway	700.1	12	58.34	4.98*

Table 4.13: Multilevel ANOVA F-test Results at 130% Current Traffic Volume
(* denotes significance at the α=0.05 level)

With the ANOVA results showing differences in the parameter levels, it is now necessary to examine these differences. This is done using a post hoc analysis. Tukey's honest significant difference test is used to do these pairwise comparisons. The results from this test for the headway at the three traffic volumes are shown in Figures 4.10-4.12. As the traffic volume on the roadway increases each of the headway values becomes more significant. In both the 100% and 115% PHV scenarios the 0.50 second headway is not significantly different from the 0.75 second case, though in the 130% PHV scenario the 0.50 second headway is significantly different from the 0.75 second case. These results are shown in the first mean difference (I-J) value in each of the three figures, with an asterisk denoting significance at the α=0.05 level. This effect of traffic volume can be seen in the fact that each headway level is significantly different from the other three with the 130% PHV. These results show that as the traffic volume increases the chosen headway level will have a greater effect on results.

	0.5	0.75	1	1.25
0.5	-	-1.06	-3.01*	-5.24*
0.75	1.06	-	-1.95	-4.18*
1	3.01*	1.95	-	-2.23
1.25	5.24*	4.18*	2.23	-

Table 4.14: Tukey's HSD Results for Headway at the Current Traffic Volume
(* denotes significance at the α=0.05 level)

	0.5	0.75	1	1.25
0.5	-	-2.15	-5.91*	-18.67*
0.75	2.15	-	-3.76	-16.53*
1	5.91*	3.76	-	-12.77*
1.25	18.67*	16.53*	12.77*	-

Table 4.15: Tukey's HSD Results for Headway at 115% Current Traffic Volume
(* denotes significance at the α=0.05 level)

	0.5	0.75	1	1.25
0.5	-	-4.41*	-10.52*	-34.38*
0.75	4.41*	-	-6.11*	-29.97*
1	10.52*	6.11*	-	-23.86*
1.25	34.38*	29.97*	23.86*	-

Table 4.16: Tukey's HSD Results for Headway at 130% Current Traffic Volume
(* denotes significance at the α=0.05 level)

Tukey's honest significant difference test is also used on the market penetration parameter levels. The results from this test are shown for the three traffic volumes in Figures 4.13-4.15. The 20% market penetration level is always significantly different from the other levels of this parameter. With such a small number of trucks of the roadway being DATP enabled the added benefit of the technology is hindered. Similar to the headway parameter an increase in traffic volume leads to an increase in the significance of the parameter levels. For both the 100% and 115% PHV there is no significant difference between the 80% and 100% market penetration levels. Whereas for the 130% PHV these two market penetration levels are significantly different. At the 130% market penetration level all of the market penetration parameter levels are significantly different from one another.

	20	40	60	80	100
20	-	2.72*	4.35*	5.65*	7.18*
40	-2.72*	-	1.64	2.93*	4.46*
60	-4.35*	-1.64	-	1.29	2.83*
80	-5.65*	-2.93*	-1.29	-	1.53
100	-7.18*	-4.46*	-2.83*	-1.53	-

Table 4.17: Tukey's HSD Results for Market Penetration at the Current Traffic Volume
(* denotes significance at the α=0.05 level)

	20	40	60	80	100
20	-	4.98*	7.47*	9.96*	12.45*
40	-4.98*	-	2.49	4.98*	7.47*
60	-7.47*	-2.49	-	2.49	4.98*
80	-9.96*	-4.98*	-2.49	-	2.49
100	-12.45*	-7.47*	-4.98*	-2.49	-

Table 4.18: Tukey's HSD Results for Market Penetration at 115% Current Traffic Volume
(* denotes significance at the α=0.05 level)

	20	40	60	80	100
20	-	5.87*	10.21*	15.15*	17.94*
40	-5.87*	-	4.34*	9.28*	12.07*
60	-10.21*	-4.34*	-	4.94*	7.73*
80	-15.15*	-9.28*	-4.94*	-	2.79
100	-17.94*	-12.07*	-7.73*	-2.79	-

Table 4.19: Tukey's HSD Results for Market Penetration at 130% Current Traffic Volume
(* denotes significance at the α=0.05 level)

4.6 – Summary

This chapter presented the results of the traffic microsimulation used to model the traffic effects of potential implementation of DATP technology on a section of I-85. The results were then statistically analyzed using both a t-test and a multilevel ANOVA. The conclusions that can be made from these results will be discussed in the next chapter.

Chapter 5 – Conclusions and Recommendations

5.1 – Conclusions

This study focused on finding the traffic impacts of driver assistive truck platooning using traffic microsimulation. The parameters of average speed and travel time benefit have shown what effects DATP can have on roadways. As the traffic flows were increased, the positive effect of the technology also increased on the roadway. As the amount of delay from all vehicles on the roadway is increased, there is a greater potential for the DATP technology to reduce this delay. This is true up to where the volume to capacity ratio approaches 1. At this point where congestion on the roadway becomes heavy there is not enough movement on the roadway for DATP's positive impact to take effect.

The advent of CACC technology on roadways will allow freeways to operate more efficiently. The use of technology to decrease the delay on roadways may allow state transportation agencies to move away from, or at least delay the necessity of, expensive widening projects. The greatest added benefit for traffic flow will be evident during the peak hours of traffic on roadways. These positive effects will be available without the necessary construction delay on these roadways that typically accompany widening projects. DATP allows for one driver to make the decisions for two or more vehicles on the roadway. These vehicles become connected and will move through the roadway as if they were one vehicle as DATP is initiated. This will remove a large amount of decision making from the roadway users. When the number of decisions drivers have to make decrease, there should also be a decrease in crashes.

Without these disturbances on the roadways, the overall impact will be more positive than that which was shown through the simulation.

It will be necessary for guidelines to be set for drivers that use this technology on roadways. This will allow for the large number of automakers on the road to have standard specifications for platooning. Two agencies that will have input into this are the Federal Highway Administration (FHWA) and National Highway Traffic Safety Administration (NHTSA). Using heavy-duty trucks to introduce this technology onto the roadway will allow for these agencies to have much greater control than would be possible with passenger vehicles. There will need to be a certain percentage of DATP capable vehicles on the roadway before its positive benefit is observed on the roadway. The government can mandate that trucks become compliant with this technology much faster than would be possible with passenger cars. Using this subsection of total vehicle miles to implement this technology onto the roadway will allow agencies to understand and better govern platooning when it is introduced to the full traffic stream. As the percentage of vehicles on the roadway that can join platoons increase the added benefit to the roadway measures of effectiveness will only increase.

5.1.1 – Model Results

The statistical results from the traffic microsimulation completed show trends that would be beneficial in choosing the market penetration and headway necessary for implementation on the roadway. The traffic volume on a roadway will have a large effect on the impact of DATP implementation. Nissan has made clear statements that they expect a full speed highway automation system by 2020 (Hutton, 2014).Other carmakers have also committed to high levels of automation in this time frame. With DATP deployment happening in the near future, the discussion of model results will focus on the current peak hour. The 20% market penetration level is significantly different from all the other penetration levels based on the ANOVA testing. Each of the other 4 market penetration levels have at least one penetration level where its mean difference is not significant. It is always the next highest level of market penetration (40% and 60%, 60% and 80%, 80% and 100%). The same linkage between the parameter levels is shown in the headway results (0.50 and 0.75, 0.75 and 1.00, 1.00 and 1.25). The information from these statistical results can give added information into what levels of DATP implementation technology would give the needed added benefit to the roadway. The market penetration necessary for implementation must be greater than 20%. The headway chosen must be beneficial to the roadway users and safe for implementation on the roadway. For this reason, the levels of 0.50 and 0.75 seconds should not be implemented until roadway users become more comfortable with these vehicles. With 1.25 seconds possible with lesser technologies such as adaptive cruise control, the recommended level of headway for initial implementation will be 1.00 seconds. In addition to the traffic benefits, this implementation will also allow for fuel savings for the vehicles using DATP technology. This will spur companies to begin using the technology, especially those companies with large truck fleets that will see large monetary savings.

5.2 – Recommendations

Microsimulation platforms are very beneficial for transportation engineers as they allow for the establishment of low cost estimation of the effects of a change to a roadway network. As these platforms are used in new and complex situations the results must be supplemented with field testing. As the DATP technology has been researched thoroughly, field testing is becoming more prevalent in the field. A large amount of this testing has not been in mixed traffic, though this is also becoming more prevalent. As mixed traffic testing is increasing, the resultant effects on traffic must be compared to those of the simulation environment.

The site specific conditions of a roadway must be considered before results from multiple simulations are compared. The number of lanes, geometric design, characteristics of the traffic in the area, and prevalent weather conditions may vary the benefits of DATP technology on roadways. Generalizing these results will be difficult due to these site specific conditions. As automated vehicles become more prevalent in the field simulation models will need to be updated compensate for changes in driver behaviors.

5.3 – Future Work

There are many areas where additional research will allow for added understanding of the benefit of DATP technology. Adding to the length of platoons will significantly change traffic flow on roadways. Three-truck platoons will affect traffic flow much differently than the two-truck focus of this research. Issues such as length of platoons denying vehicles to traverse lanes will be a key issue.

Varying the percentage of heavy duty trucks in the simulation will also have impacts on the results. In this study, the percentage was set to the percentage of trucks observed during the peak hour of traffic. There are many other areas in the nation where this peak hour truck percentage varies. In comparison to focusing on the peak hour of total traffic, investigation of the peak hour of truck volume could also prove beneficial.

Investigation of DATP on different roadway types is another key issue. Freeways are the most controlled road type and allow for platoons to move through segments without having to stop. Examining DATP on a roadway such as a rural arterial, which would not have full control of access, and would have occasional traffic signals will show if this technology has potential ubiquitous use or if it should be confined to controlled access highways.

This study focused on platooning in mixed traffic; DATP may also be established on roadways in restricted lanes. This may be especially beneficial in situations where the market penetration of the technology is still relatively low.

References

Alabama Department of Transportation (ALDOT). (2014). Alabama Traffic Data. http://algis.dot.state.al.us/atd/default.aspx. Accessed July 7 2015.

Audi. (2011). Adaptive Cruise Control with Stop & Go Function. http://www.audi-technology-portal.de/en/electrics-electronics#filter=driver-assistant-systems. Accessed March 24 2015.

Arnaout, G. M., & Bowling, S. (2014). A progressive deployment strategy for cooperative adaptive cruise control to improve traffic dynamics. *International Journal of Automation and Computing*. Vol.11(1). p.10–18.

Bishop, R. (2012). Public Notice: Smart Followers Needed. Thinking Highways. Vol. 7(2). p. 8

Bishop, R. (2013). Are We In Need Of a System That Monitors Our Driver-Monitoring System?. Thinking Highways. Vol. 8(2) p. 56

BMW. (2014). Active Cruise Control. http://www.bmw.com/com/en/insights/technology/technology_guide/articles/active_cruise_control.html. Accessed March 24 2015.

Deng, Q. & Ma, X. (2015). A Simulation Platform for Autonomous Heavy-duty Vehicle Platooning in Mixed Traffic. *Paper presented at 2015 Transportation Research Board Annual Meeting.*

Devitt, S., Shanker, R., Jonas, A., Huberty, K., Flannery, S., Greene, W., Swinburne, B., Locraft, G., Wood, A., Weiss, K., Moore, J., Schenker, A., Jain, P., Ying, Y., Kakiuchi, S., Hoshino, R., Humphrey, A. (2013). Autonomous Cars Self-Driving the New Auto Industry Paradigm. http://www.morganstanley.com/articles/autonomous-cars-the-future-is-now/. Accessed March 4 2015.

Dowling, R., Skabardonis, A., Alexiadis, V. (2004). Traffic Analysis Toolbox: Volume III: Guidelines for Applying Traffic Microsimulation Software. FHWA-HRT-404.

FHWA. (2013). Public Road Mileage – VMT – Lane Miles 1920-2013. http://www.fhwa.dot.gov/policyinformation/statistics/2013/vmt421c.cfm. Accessed May 1 2015.

Hutton, P. (2014). A Driverless Future?. Thinking Highways. Vol. 9(3). p. 4-11

McTrans Center. (2010). CORSIM Users Manual.

Nieuwenhuijze, M., van Keulen, T., Oncu, S., Bonsen, B., Nijmeijer, H. (2012). Cooperative Driving With a Heavy-Duty Truck in Mixed Traffic : Experimental Results. *IEEE Transactions on Intelligent Transportation Systems.* Vol.13(3), p.1026–1032.

NIST (2012). NIST/SEMATECH e-Handbook of Statistical Methods. http://www.itl.nist.gov/div898/handbook. Accessed May 1 2015.

Ploeg, J., Serrarens, A., Heijenk, G. (2011). Connect & Drive: design and evaluation of cooperative adaptive cruise control for congestion reduction. *Journal of Modern Transportation*. Vol.19(3). p.207–213.

Rakha, H. & Crowther, B. (2002). A Comparison of the Greenshields, Pipes, and Van Aerde Car-Following and Traffic Stream Models. *Transportation Research Record: Journal of the Transportation Research Board*. Vol.1802. p.1–21.

Riemann, R., Baur, M., Fullerton, M. (2012). Parameter Sensitivity Analysis of a Cooperative System by Means of Microscopic Traffic Simulation. *Paper presented at the 15th International IEEE Conference on Intelligent Transportation Systems.*

Schakel, W. J., van Arem, B., Netten, B. (2010). Effects of Cooperative Adaptive Cruise Control on Traffic Flow Stability. *Paper presented at the 13th International IEEE Conference* on *Intelligent Transportation Systems.*

Shladover, S. E. (2012). Dreaming With Deadlines. Thinking Highways. Vol. 7(3). p. 20-22.

Shladover, S. E., Su, D., Lu, X. (2012). Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. *Transportation Research Record: Journal of the Transportation Research Board.* Vol. 2324. p. 63-70

Van Arem, B., van Driel, C., Visser, R. (2006). The impact of Co-operative Adaptive Cruise Control on traffic flow characteristics. *IEEE Transactions on Intelligent Transportation Systems.* Vol. 7(4), p.429-436.

Varotto, S. F., Hoogendoorn, R., van Arem, B., Hoogendoorn, S. (2014). Human Factors of Automated Driving: Predicting the Effects of Authority Transitions On Traffic Flow Efficiency. *Paper presented at the 2nd Transportation, Infrastructure, and Logistics Internal PhD Conference.*

Wayland, Michael. (2015). "Adaptive Cruise Control Goes Mainstream." *Detroit News*. http://www.detroitnews.com/story/business/autos/2015/03/03/adaptive-cruise-control-growing/24352141/. Web. Accessed June 8 2015.

Zhang, W. (1996). Minimum Reliability Requirements on Automated Vehicles for a Safe and Reasonably Efficient Automated Highway System. *Paper presented at 1996 Vehicle Navigation and Information Systems Conference.*

Zhang, W., Misener, J. A., Chan, C., Zhou, K., Li, J. (2014). Feasibility Assessment of A Truck Automation Deployment Framework. *Paper presented at 2014 Transportation Research Board Annual Meeting*.

Zhao, L. & Sun, J. (2013). Simulation Framework for Vehicle Platooning and Car-following Behaviors Under Connected-vehicle Environment. *Procedia - Social and Behavioral Sciences*. Vol.96. p.914–924.

Appendix

Headway	Market Penetration	Mean Delay	Std. Dev.	One Sample T	P-Value
1.25	100	9.875	3.7	-4.323105191	0.049563
1	100	7.811	1.7	-11.51202475	0.007461
0.75	100	6.45	0.9	-24.36418136	0.00168
0.5	100	5.851	2.5	-9.186104663	0.011644
1.25	80	11.258	2.6	-5.230793439	0.034659
1	80	9.374	1.2	-14.05270555	0.005026
0.75	80	8.453	2.6	-7.099409791	0.019269
0.5	80	7.021	3.9	-5.368913388	0.032985
1.25	60	13.134	3.6	-2.875204341	0.102672
1	60	10.936	1.8	-7.865435167	0.015783
0.75	60	9.03	3.3	-5.290627921	0.033919
0.5	60	8.191	1.8	-10.50681265	0.008937
1.25	40	15.011	2.8	-2.535598664	0.126655
1	40	13.142	4	-2.584219805	0.122767
0.75	40	10.319	1.7	-8.956740382	0.012237
0.5	40	9.362	1.6	-10.55251955	0.008861
1.25	20	18.763	3.6	-0.166950453	0.882762
1	20	15.623	4.1	-1.473088089	0.278625
0.75	20	12.899	2.6	-4.13760291	0.053746
0.5	20	11.416	2	-6.663199457	0.02179

Table A.1 – Full t-test Results for the Current Traffic Volume

Headway	Market Penetration	Mean Delay	Std. Dev.	One Sample T	P-Value
1.25	100	20.775	2.8	-16.02456292	0.003872
1	100	11.909	1.5	-40.15009242	0.00062
0.75	100	9.298	2.2	-29.4306924	0.001153
0.5	100	7.806	2.3	-29.27467091	0.001165
1.25	80	24.929	0.7	-53.81976731	0.000345
1	80	14.291	3.7	-15.16199827	0.004322
0.75	80	11.158	2.4	-25.63579533	0.001518
0.5	80	9.367	1.8	-35.90445099	0.000775
1.25	60	29.084	3	-10.15905534	0.009551
1	60	16.673	2.4	-21.65568691	0.002126
0.75	60	13.017	0.8	-72.88253292	0.000188
0.5	60	10.928	3.6	-17.20118902	0.003363
1.25	40	33.239	1.8	-12.93360828	0.005925
1	40	19.054	2.5	-19.13985424	0.002719
0.75	40	14.877	2.1	-26.2306723	0.00145
0.5	40	12.49	5.2	-11.38823406	0.007623
1.25	20	41.549	3.4	-2.613868439	0.120478
1	20	23.818	1.3	-30.46011197	0.001076
0.75	20	18.596	1.7	-28.61347934	0.001219
0.5	20	15.612	2.4	-22.4213977	0.001983

Table A.2 – Full t-test Results for 115% Current Traffic Volume

Headway	Market Penetration	Mean Delay	Std. Dev.	One Sample T	P-Value
1.25	100	33.776	3	-20.3827739	0.002398
1	100	16.807	3.5	-25.86842625	0.001491
0.75	100	13.027	1.6	-60.67915245	0.000271
0.5	100	10.249	3.7	-27.54007596	0.001316
1.25	80	38.457	1.3	-40.80045529	0.0006
1	80	21.174	3.9	-21.27580154	0.002202
0.75	80	13.411	4.8	-20.08782008	0.002469
0.5	80	11.987	3.9	-25.35589148	0.001552
1.25	60	49.286	3.6	-9.52339269	0.010847
1	60	23.53	3.5	-22.54140408	0.001962
0.75	60	17.856	3.3	-26.88562744	0.001381
0.5	60	14.102	5.9	-16.13977785	0.003817
1.25	40	54.041	3.8	-6.854818972	0.020626
1	40	28.691	4	-17.48895002	0.003253
0.75	40	23.45	3.8	-20.79828378	0.002304
0.5	40	15.952	1.1	-83.65490482	0.000143
1.25	20	67.551	2.1	-1.261097945	0.334452
1	20	33.614	3.5	-17.55111827	0.003231
0.75	20	25.508	3.7	-20.39700481	0.002395
0.5	20	18.936	2.5	-34.74078228	0.000828

Table A.3 – Full t-test Results for 130% Current Traffic Volume

Source	Type III Sum of Squares	df	Mean Square	F
Corrected Model	14143.02	19	744.37	8.79*
Intercept	60920.19	1	60960.19	719.49*
Market Penetration	10063.97	3	3354.66	39.62*
Headway	3466.47	4	866.62	10.24*
MP * Headway	612.59	12	51.05	0.603

Table A.4 – Multilevel ANOVA Results for the Full Dataset

Headway (i)	Headway (j)	Mean Difference (i-j)
0.50	0.75	-2.54
	1.00	-6.48*
	1.25	-19.43*
0.75	0.50	2.54
	1.00	-3.94
	1.25	-16.89*
1.00	0.50	6.48*
	0.75	3.94
	1.25	-12.95*
1.25	0.50	19.43*
	0.75	1689*
	1.00	12.95*

Table A.5 – Tukey's HSD Results for Headway for the Full Dataset

Market Penetration (i)	Market Penetration (j)	Mean Difference (i-j)
20	40	4.52
	60	7.34*
	80	10.25*
	100	12.52*
40	20	-4.52
	60	2.82
	80	5.73
	100	8.00*
60	20	-7.34*
	40	-2.82
	80	2.91
	100	5.18
80	20	-10.25*
	40	-5.73
	60	-2.81
	100	2.27
100	20	-12.52*
	40	-8.00*
	60	-5.18
	80	-2.27

Table A.6: Tukey's HSD Results for Market Penetration for the Full Dataset