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Evaluating the Performance of Cooperative Merging Assistance System for Aging Drivers

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EVALUATING THE PERFORMANCE OF COOPERATIVE MERGING ASSISTANCE SYSTEM FOR AGING DRIVERS

By

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LIST OF ACRONYMS

CV	Connected Vehicles
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
Car2X	Car-to-Devices
DSRC	Dedicated Short-Range Communication
COM	Component Object Model
API	Application Programming Interface
CMAS	Cooperative Merging Assistance System
CMA	Cooperative Merging Assistance
MOEs	Measures of Effectiveness
HCM	Highway Capacity Manual
LOS	Level of Service
FDOT	Florida Department of Transportation
MSDR	Minimum Safety Distance Requirement
VISs	Vehicle Interaction States

ABSTRACT

Freeway merging maneuvers demand considerable attention by drivers and are among the more complex operations drivers must perform on freeways. Aging drivers, a growing population in the United States, face added challenges when merging. This study utilized Vissim models created in a previous study that modeled the behavior of aging drivers during freeway merging. An algorithm for Cooperative Merging Assistance System (CMAS) that utilizes Connected Vehicle (CV) technology was developed in this study. The Vissim models were created for two interchanges on I-75 in Fort Myers, Florida, each with different geometric characteristics. Acceleration lane lengths of 1000ft and 1500ft were analyzed in this study, and the CV environment was created in Vissim through the Component Object Model (COM) Interface. A sensitivity analysis was conducted by varying CV penetration rates, composition of aging on-ramp drivers, and mainline and on-ramp traffic flows to analyze the effects of CV technology under different levels of service (LOSs). Merging location, merging speed and vehicle interaction states (braking for lane change, emergency stop and cooperative braking) together with deceleration rate were the measures of effectiveness (MOEs) considered. Findings showed the number of aging drivers merging late onto the freeway can be decreased by up to 60.0% when CMAS was employed, while there was no significant change in merging speed at 95% confidence level when CMAS was employed. Furthermore, the results showed that CMAS reduced the percentages of aging drivers braking for lane change or emergency stop and also hard braking by up to 100% for low traffic conditions (LOS A and B). A maximum reduction of 82.2% was observed for cooperative braking of mainline vehicles when CMAS was employed. The reductions in interaction states were significant at 95% confidence level according to Mann-Kendall trend test.

Keywords: Aging Drivers, Connected Vehicles, Cooperative Merging

CHAPTER 1 INTRODUCTION

Background

The size of elderly population is growing in most areas of the world. Statistics shows that the population in United States (U.S) is growing older. In 2050, the older population aged 65 and over is estimated to be almost twice the aging population estimates of year 2012, (Ortman, Velkoff, & Hogan, 2014). The American Community Survey Report – 2016, has estimated the number of people in the United States aged 65 and over as 49.2 million. More than half (28.7 million or 28%) of this older population were aged between 65 and 74, around 14.3 million or 29 percent were aged between 75 and 84, and those aged 84 and older were around 6.3 million or 13 percent (Roberts, Ogunwole, Blakeslee, & Rabe, 2018). According to the forecast, the aging population will continue to increase, figure 1.1.

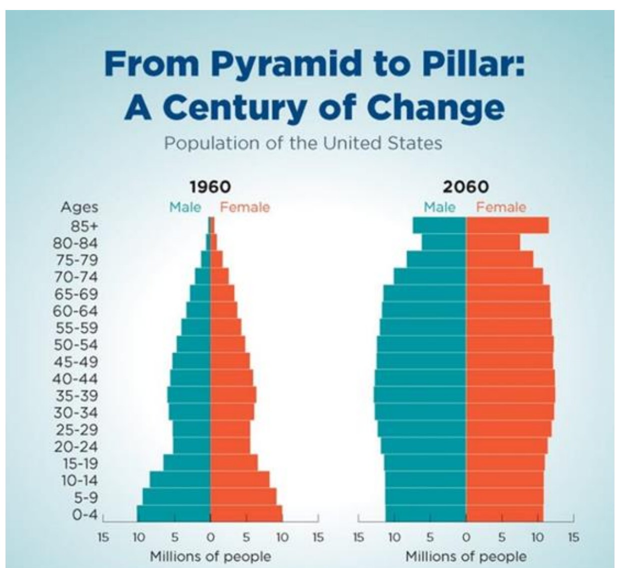


Figure 1.1: Projections of Population of the United States (Source: National Population Projections, 2017)

With this significant increase of older population, it's obvious that the number of older drivers will increase too. By 2050, out of four drivers with license, one licensed driver is expected to be an older driver. Florida is among many states in the United States whose population of 65 and older is expected to reach 20% in this decade. United States is also considered as a mobile society, adult drivers do drive for different reasons such as volunteer activities and gainful employment, social and recreational needs, and cross-country travel (American Geriatrics Society & A. Pomidor, 2016). Thus, in the future it is expected to have more miles travelled by older drivers than it is today. From experts' perspective, based on the fact that Florida leads the country with over 18 percent of the population over the age of 65, it is expected that over 27 percent of Florida's population will be over the age of 65 by the year 2030 (Safety Mobility for Life Coalition, 2018). This should mean that, Florida's licensed drivers will also be getting older. According to a national Transportation Research Group (Carolina, 2018), the change in number of 65+ licensed drivers between 2012 and 2016 was 14% with the change in fatalities involving at least one 65+ driver in the same period was 41%, whereby 240 drivers were killed in 2012 and 357 killed in 2016 (almost a death every day of the year).

Older drivers do experience declining vision; slowed decision-making and reaction times; exaggerated difficulties when dividing attention between traffic conflicts and other important sources of motorist information; and reductions in strength, flexibility, and general fitness (Brewer, Murillo, & Pate, 2014). Merging on freeway is one of complex scenarios faced by older drivers due to some difficulties on merging maneuver (Lwambagaza, 2016). The vehicles on mainline travel with higher speed based on speed limit, on-ramp vehicles need to find an acceptable gap to enter the mainstream. Sometimes if vehicles on the freeway are forced to reduce speed so as to accommodate merging vehicles, a wave is generated and can propagate upstream and lead to flow breakdown. On the other side, if the front vehicle takes longer time to initiate merging maneuver, the denser the traffic it might get on-ramp.

To help older drivers in merging maneuvers, Connected Vehicles (CVs) technology has emerged as a potential option. The connected vehicles are used to communicate information about their speed and position. CVs technology is sought to help increase capacity of existing transportation networks but also the benefits in most important aspects of roadside safety for motorists through the development of an overall Intelligent Transportation System (Jadaan, Zeater, & Abukhalil, 2017). Since these connected vehicles can communicate, hence they can cooperate.

One study explored the cooperative behavior that enhances the perception of environments not only through its own sensors, but through the sensors of other vehicles (Radu Popescu-Zeletin & Rigani, 2010). In the study, some examples of cooperative applications discussed was Cooperative Merging. Furthermore, the study discussed the benefits of cooperative behavior on highways. One of those benefits is that, cooperative behavior can provide a possible solution to achieve applications such as collision avoidance or automatic merging of vehicles on the highways, which without vehicular communication it is only a dream. Thus, having a system that makes vehicles cooperate, will greatly enhance older drivers merging maneuver on freeways.

A cooperative merging system can be used to compensate the deficiencies that older drivers do possess and ad-on abilities on the merging maneuver. As defined by (Radu Popescu-Zeletin & Rigani, 2010) Cooperative Merging Assistance (CMA) is a system that provides a safer, automatic way for a vehicle to join a flowing traffic (e.g. a highway entry). It allows vehicles to join ("on-ramp") the traffic without disrupting the flow of the traffic. It eliminates drivers' misunderstandings by letting the vehicles decide the best way to join, based on the exchange of information (such as velocities and positions) between vehicles. A Cooperative Merging Assistance (CoopMA) for on-ramps can utilize intelligent vehicles capable of V2I communication

(Scarinci, Hegyi, & Heydecker, 2017). The basic idea of CoopMA is to coordinate the release of on-ramp vehicles with gaps on the main carriageway created for facilitating the merging. These gaps can be created by rearranging the position of the vehicles present on the near-side lane, i.e. the lane close to the on-ramp. It is obvious that a Cooperative Merging Assistance System is safe compared with human operations.

Despite having different freeway merging assistance systems using CV technology being developed by different studies, none of them studied the benefits of a freeway cooperative merging assistance system to aging drivers. This study is aimed in developing an algorithm using the connected vehicles technology to enhance aging drivers' freeway merging maneuver. A detailed analysis of the CV based merging cooperative system, herein referred to as Cooperative Merging Assistance System (CMAS) is conducted and the benefits on safety and operations are evaluated.

Study Objectives

This study has two objectives triggered by the increase in population of older drivers, miles traveled by older drivers, challenges faced by older drivers and emerging technologies which can compensate the challenges of aging drivers. These objectives are:

- To evaluate the performance of CMAS under different geometries of the acceleration lanes
- To use surrogate safety measures to evaluate the safety of CMAS

Study Benefits

The findings in this study add to the knowledge on how CV technology works with different geometric characteristics of acceleration lanes and offers a platform for further research on aging driver behaviors and the performance of cooperative merging assistance systems. The approach used in this study also contributes to the existing body of knowledge on surrogate safety measures and adds value on the outputs of the microscopic simulations in evaluating the safety of systems being developed today.

Study Approach and Overview

In this study, the Vissim microscopic simulation tool has been used to conduct sensitivity analysis to evaluate the potentials of CMAS. The Vissim models were adopted from the previous study that modeled aging drivers' behavior on freeway merging for the same site locations as in this study. The connected vehicles environment was created in Vissim through the Component Object Model (COM) interface, whereby V2I (vehicle-to-infrastructure) and V2V (vehicle-to-vehicle) wireless communication between connected vehicles were modeled using the Car2x (car-to-anything) Application Programming Interface (API). The Measures of Effectiveness (MOEs) of this study included merging location, merging speed and aging driver interaction states together with deceleration rates (hard braking). Z-test and Mann-Kendall trend test were used in statistical analysis to check for significance of the results obtained after sensitivity analysis.

Chapter 2 provides a thorough review of previous studies on aging drivers, freeway merging maneuvers, and cooperative merging assistant systems which utilized connected vehicles technology. Chapter 3 provides description on the site locations and the methodology adopted in this study. Chapter 4 shows the evaluation on the operational characteristics of aging drivers on different geometry of acceleration lanes in a connected vehicle environment. Chapter 5 in this study provides description on how aging drivers' interaction states and deceleration rates (hard braking) were used as Surrogate Safety Measures (SSMs) to evaluate the safety of the CMAS. These interaction states were obtained in Vissim vehicle record files after conducting a sensitivity analysis. A concluding chapter 6 ties the previous chapters together and presents findings in summary form together with the recommendations for future studies.

CHAPTER 2 LITERATURE REVIEW

Aging Drivers' Difficulties on Traffic Operations

Driving is associated with several tasks which make it complex. Some of the tasks like motor and cognitive need to be performed either in quick succession or simultaneously. Drivers' reactions in relation to vehicular parameters, other motorists and pedestrians' behaviors in addition to varying weather conditions, road geometry and surface are of vital importance (Hulse, Xie, & Galea, 2018). These challenges may make things worse especially for aging drivers.

Some of the challenges that are associated with aging like sensory, perceptual and cognitive pose difficulties to the elderly on their driving (Laosee, Rattanapan, & Somrongthong, 2018). Processing of information, remembering and judging driving events such as distance of oncoming traffic decrease slowly at age 55 and above (MDOT, 2014). The declining of these specific skills such as vision, memory, strength, flexibility, and quick reaction time is specific for each person meaning that it differs from person to person. About 35% of people aged 65 and above have some type of disabilities (i.e., difficulty in hearing, vision, cognition, ambulation, self-care, or independent living) (ACL, 2018). Situations that include complex visual searches, and information from different sources that need a rapid processing under divided attention conditions have more risk for older drivers (Stutts, Martell, & Staplin, 2009).

In comparison to young drivers, older drivers are at more risk due to frailty, they do also have less agility judging time thus increased risk of crashing due to slower reaction times (Chevalier et al., 2016). Some areas on highways are associated with significant oscillations where drivers are needed to decelerate at higher rate. Though the experience may have benefit for older drivers in managing their speed conservatively, the rapidly speed change may pose more crash risk to old drivers and it can result to collision with another vehicle, and a rear end crash is most likely to occur (Keay et al., 2013).

Though the risk for older drivers differs depending on the age group, whereby age group of 60 to 69 face low risk compared to substantial crash experience for drivers at age 70 to 79 who also face lower risk as compared to age 80 and older. In addition, about 69 percent of the population 85 and over had at least one type of disability, compared with just 9 percent of the population under the age of 65, figure 2.1. During left turn maneuver, the risk of being involved in a crash is higher for aging drivers (65 and older) as compared to young drivers (Chandraratna & Stamatiadis, 2003). In addition, due to problems in vision, older drivers are 1.65 more likely to be involved in left turn crashes compared to young drivers. In terms of crash type, when an older driver is involved in a crash related to a left turn, the probability of fatal crash is 2.41 higher than the younger driver, the difference is not significant for injury only crashes and property damage crashes. Generally, around age 70 older drivers' risk to themselves and other road users is higher compared to the middle age group (Tefft, 2008). Comparing to lowest risk drivers, older drivers pose more risk to their passengers, occupants of other vehicles, and non-motorists. Driver's age has an effect on traffic performance measures and safety (Ulak, Ozguven, Moses, Abdelrazig, & Sando, 2018). A Microsimulation based analysis for an unsignalized intersection shows that, queue lengths, travel times and delays are affected by different compositions of aging drivers. Furthermore, the results based on the Surrogate Safety Assessment Model (SSAM) indicated that, the higher conflict risk in traffic stream is associated with the higher composition of aging drivers in the traffic stream.

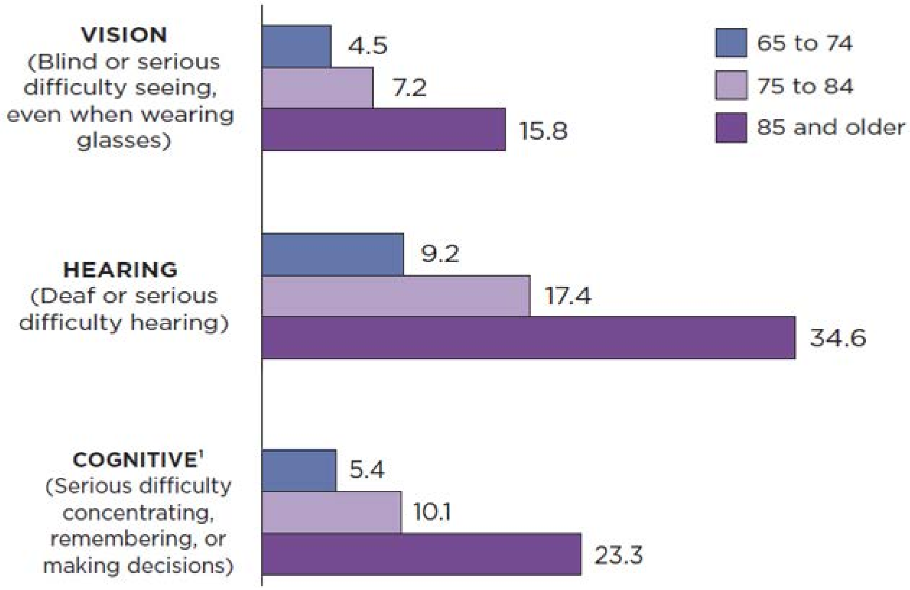


Figure 2.1: Disabilities by Age and Type: 2016 (Source: Roberts, Ogunwole, Blakeslee, & Rabelsluu, 2018)

Merging Maneuver on Freeways

Merging Area

Merging maneuvers on major freeways are facilitated by ramps which can be linked with an acceleration lane (Transportation Research Board, 2000). The acceleration lane length has effects on the performance of traffic operations. Long acceleration lane provides enough time for the merging vehicles to find an acceptable safe gap in the mainline but also long acceleration lanes are associated with low crash frequencies while, short lanes or taper connections provide on-ramp vehicles limited opportunity to accelerate before performing the merging maneuver (AASHTO, 2011; Transportation Research Board, 2000). The speeds of vehicles on ramp and on the mainline traffic and the oscillations of the merging vehicle influence the lengths of the ramp (Ran, Leight, & Chang, 1999). During merging on freeway merge area, each on-ramp vehicle looks for gap in the rightest lane in the freeway so that it can join the freeway traffic (Transportation Research Board, 2000).

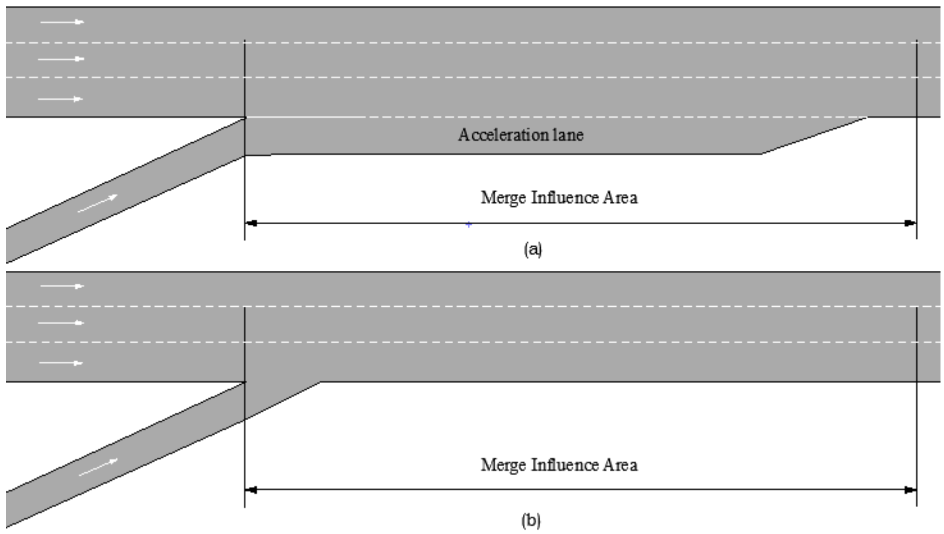


Figure 2.2: Freeway Merging Area; (a) with an Acceleration Lane; (b) with Taper Connection

Merging Maneuver; State-of-the-Art

The performance of highways can be affected by merging areas. The on-ramp vehicle intending to merge when traveling on the acceleration lane, it will look for an available gap to enter the mainline until there is enough space to merge (Y. Wang, Wenjuan, Tian, Lu, & Yu, 2011). The complexity of the merging maneuver can result in a change in the operational characteristics of the drivers about to merge. Merging on freeways is a typical lane changing scenario with the special feature of the reduction in the number of lanes which makes the merging maneuver a mandatory traffic operation. Also, the merging maneuver can be regarded as the operation of a vehicle from an entry lane performing merging into the mainline between two vehicles in a platoon (Yun-Lu & Hedrick, 2000). The freeway merging maneuver where there is an acceleration lane can also be considered as a mandatory lane change and can be divided into three categories which are merging in between two vehicles in a platoon, merging in front of a platoon and merging behind a platoon (Pueboobpaphan, Liu, & Van Arem, 2010). At merging areas, vehicles coming from entrance ramps joining the freeway are competing for space with traffic already flowing along the mainline freeway lanes as the merging vehicles try to find gaps in the traffic stream (Mergia, Eustace, Chimba, & Qumsiyeh, 2013; Transportation Research Board, 2000).

The condition of traffic in the target lane significantly affect the on-ramp vehicles' selection of the gap and the tactics during merging maneuver (Wan, Ran, Zhang, Yang, & Jin, 2014). Both drivers, the one on mainline and the other on the ramp must be able to interpret the situation and anticipate the operation of the traffic around them so as to efficiently complete the complex maneuver (Milanes, Godoy, Villagra, & Perez, 2011). The drivers about to merge into the freeway, before making decisions based on their speed and position, must process the information regarding the traffic and roadway (Sarvi, Kuwahara, & Ceder, 2004). The merging vehicle needs to travel with the same speed and acceleration as that of the mainline traffic so as to merge without causing perturbation in the mainline and thus minimize the possibility of crashes (Y. Wang et al., 2011). The on-ramp vehicle, merging in the mainline can cause traffic instability to certain a degree and the resulting magnitude of the turbulence will be dependent on the maneuverability of the on-ramp vehicle (Kondyli & Elefteriadou, 2011).

The merging maneuvers that can be performed without interactions between merging vehicles and vehicles in the mainline are referred to as free merges. The other maneuver is the one whereby the vehicle in the mainline changes lane or slows down to yield to the vehicle on the ramp by creating an acceptable gap and this is referred to as cooperative merge. The merging maneuver can also be forced merge which results in conflicts as the mainline vehicle is forced by the merging vehicle to either slowdown or change lane. The execution of the merging maneuver is different under the congested condition whereby merging is a complex mechanism as acceptable gaps for merging are rarely available compared to the uncongested condition where the gaps are available (Choudhury, Ramanujam, & Ben-Akiva, 2009).

In order to safely join the freeway traffic, the driver on the ramp is required to observe the acceptable safety gap in the mainline and adjust his/her speed accordingly (AAA Club, 2005). A vehicle on the acceleration lane is required to yield the right of way to the traffic on the freeway, and for safety reasons it is advised to avoid stopping on the acceleration lane unless it is necessary.

Older Drivers and Merging Maneuver

Age related problems such as a deficiency in spatial vision which relates to the timely detection and recognition of road signs and pavement markings may lead to problems for older drivers at interchanges (Staplin, Lococo, & Byington, 1998). For example, for every decade after age 25, drivers need twice the brightness at night to receive visual information. Hence, by age 75, some drivers may need 32 times the brightness they did at age 25 (AASHTO, 2011). Difficulties in freeway interchanges for older drivers is also contributed by decreased physical flexibility in the neck and upper body (Brewer et al., 2014).

A study on merging maneuver found that, drivers' behavior can be categorized into aggressive behavior, average behavior and conservative behavior (Kondyli & Elefteriadou, 2009). Drivers with aggressive behavior do not want to run out of space and they don't hesitate to cut off other vehicles during merging. Drivers that operate their vehicles depending on their status and the surrounding traffic conditions are grouped in average behavior category. Drivers possessing conservative behavior do not force the merging maneuver, they will even decelerate and wait until a large gap is created so that they can merge without disrupting the other traffic. The findings of the study also show that, the age has an impact on driver's behavior and older people were found to possess average and conservative behaviors during merging.

Elderly drivers desire large gaps in the mainline traffic and they use more time to merge as they travel at lower speed (Immers, Martens, & Moerdijk, 2015). When there is a significant amount of traffic in the mainline, elderly drivers will drive more slowly or stop on the acceleration lane and this can result in queue if there are other vehicles on the ramp following the merging elderly driver. Comparing older drivers with young drivers during merging, older drivers merge at lower speed than the speed of younger drivers (Waard, Dijksterhuis, & Brookhuis, 2009). Although the merging speed for on-ramp vehicles did not have correlation with merging position of the vehicles along the acceleration lane, age has a significant influence on merging position (Lwambagaza, 2016). Older drivers merge more at the end of acceleration lane as compared to young drivers who merge near the beginning of acceleration lane.

Connected Vehicles Technology

Overview

The application of intelligent transportation systems (ITS) is sought to provide improvement on safety and efficiency of vehicles and roadway systems (Transportation Research Board, 2000). For uninterrupted-flow highways like freeways, ITS can increase capacity of these facilities because of the reduction on headways. The drivers' comfort can be enhanced compared to the current experience in closely spacing between vehicles due to vehicle guidance systems and thus improve level of service even if there is no decrease in headways. Having the inter-vehicle communication will improve the transportation road network as vehicles will share information which will make the vehicles no longer isolated islands (Lu, Cheng, Zhang, Shen, & Mark, 2014).

Connected Vehicles (CV) Technology will be a reality in the near future. These Connected Vehicles utilize the wireless connectivity that enables vehicle-to-vehicle (V2V) communication, vehicle-to-infrastructure (V2I) or vehicle-to-anything (V2X). These communications enhance the reliability of driving operations as the perception of driver on the driving environment is improved (Talebpour & Mahmassani, 2015). Furthermore, the communications help merging vehicles and drivers on the mainline in decisions regarding the oscillations before providing gap for merging vehicle (Milanes et al., 2011). Information such as movements of vehicles and the way the drivers' operational decisions such as speed, location and oscillation are provided in detail by V2V communication while the information about the conditions of the road, weather conditions and Traffic Management Centre (TMC) are provided in detail by V2I communication (Talebpour & Mahmassani, 2015).

In connected vehicles, the drivers are the decision makers regardless of the information received. The future of road transportation systems is sought be changed as the inter-vehicle communications will be in place. Connected Car can be regarded as a game changer as it helps drivers meet their expectations while on the move (Diwanji & Karmarkar, 2012). These Connected Vehicles through control algorithms, can be coordinated using the existing information so as to improve both transportation network efficiency and safety (Ahmed, Hoque, Rios-Torres, & Khattak, 2018). The concerns on the safety of road users but also the efficiency of road transportation systems play an important role in the need to have wireless communication between vehicles (Lu et al., 2014).

Safety Improvement

The vehicle data can help not only in conserving natural resources thus providing environmental advantage, but also can improve safety (Mayer & Siegel, 2015). The vehicle can share information of its position and speed to other vehicles and thus avoid crashes (Goel & Yuan, 2015). In addition, during bad weather where inter-visibility is affected, by leveraging each other's information safety can be enhanced. Cooperatively, the vehicles can avoid crashes as they share their real time information such as speed, direction and location (CAR, 2012). The application of Dedicated

Short-Range Communications (DSRC)-based safety system which broadcasts basic safety messages at every tenth of a second can facilitate the cooperation.

Traffic Operations Improvement

The traffic congestion problem is associated with environmental, and economic cost as the vehicles continue to crowd the existing roads especially in urban areas (Lu et al., 2014). Traffic operations can be improved by the connected vehicles which can cooperate to support the management of traffic in the road network (Pau, 2013). Capacity can also be increased in the existing transportation network when utilizing CV technology as development of an overall Intelligent Transportation System (Jadaan et al., 2017). Route optimization or traffic congestion management can be well undertaken by the use of information from connected vehicles (Goel & Yuan, 2015). This information can be the location of the vehicle, the speed of the vehicles but also the driving habits associated with a vehicle (Goel & Yuan, 2015; Pau, 2013; Scarinci et al., 2017). Connected Vehicles technology is sought to help increase capacity of the existing transportation networks but also benefits the most important aspects of roadside safety for motorists through the development of an overall Intelligent Transportation System (Jadaan et al., 2017).

Merging Control

Traffic responsiveness is a key factor for merging control. Vehicle characteristics such as speed and acceleration, amount of traffic and traffic stream parameters such as gaps between vehicles must be taken into consideration in developing a merging control (Buhr, Whitson, & Brewer, 1969). By the time vehicles arrive at a merging area, sufficient headway should be ensured by the merging control system in order to allow a merging maneuver to take place smoothly without inconveniences (Milanes et al., 2011).

Merging control can be done by the control algorithm though the traffic conditions can also result to controlled merging (Scarinci & Heydecker, 2014). The merging control algorithm controls the vehicles in the merging area so that the leading vehicle and lagging vehicle can create enough gap for the on-ramp vehicle to join the mainline traffic (H. Park, Su, Hayat, & Smith, 2014). The merging control algorithm can involve only speed control while distance is used as a logical guard or distance and speed control can be involved together (Yun-Lu & Hedrick, 2000). In developing a merging control algorithm for the vehicle on the on ramp lane to merge into the mainline, all vehicles are regarded having the same dynamics (Y. Wang et al., 2011).

Cooperative Merging Assistance Systems

By means of communication, vehicles can possess a cooperative behavior which allows each vehicle to know the intentions and positions of other vehicles (Radu Popescu-Zeletin & Rigani, 2010). Information sharing can rely on the sensors of vehicles and one of the cooperative applications is cooperative merging. Cooperative merging can be performed in a system which is proactive, cooperative, having information and coordinated similar to the connected vehicles technology which can support various applications of safety on the roadway (Lu et al., 2014).

Cooperative merging assistance systems utilizes the emerging technologies to address the limitation of the current practice of ramp metering to facilitate the merging process (Scarinci et al., 2017). Cooperative merging is aimed on providing safe headways between the leading and lagging vehicles so as to allow the merging vehicle to join the traffic stream without considerable speed differential. Cooperative Merging Assistance (CMA) provides a safer, automatic way for an on-ramp vehicle to join the mainline traffic without the disruption of traffic flow (Radu Popescu-Zeletin & Rigani, 2010).

In this CMA system, drivers' misunderstandings are eliminated, and vehicles decide the best way to join based on their information, such as velocities and positions, hence make the merging maneuver safe and efficient compared to experienced drivers who at a certain point may commit a mistake. Based on the existing ramp metering infrastructure, where vehicles are released by a traffic light for the merging maneuver, a Cooperative Merging Assistance (CoopMA) can utilize the present gaps in the mainline traffic by requesting cooperation from connected vehicles in order to facilitate the merging of on-ramp vehicles (Scarinci, Heydecker, & Hegyi, 2015). CoopMA modifies the gaps between vehicles on the freeway without significant change of the vehicles' speed, shorter headways are combined into longer headway for enhancing the merging maneuver. By providing suitable gaps for merging, CoopMA reduces the time spent by merging vehicles which is thought to be a primary cause of flow breakdown at merging. Though the system does not increase main carriageway capacity, it increases the flows that can be accommodated efficiently, thus CoopMA improves traffic performance.

The CoopMA system requires Vehicle to Infrastructure (V2I) and Infrastructure to Vehicle (I2V) (Scarinci et al., 2017). In V2I, on-ramp and main carriageway vehicles provide information on the traffic state to the control centre while in I2V, the control centre releases the on-ramp vehicles and slows down cyclically the cooperative vehicles. With the help of the Dedicated Short-Range Communication (DSRC) protocol, the freeway merge assistance system also utilizes V2X technology (Ahmed et al., 2018). V2X technology is a collective term for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V21) communication technologies. In some of latest automobiles, the On-Board Units (OBU) operates safety-critical and assistive applications using V2X technology which transmits Basic Safety Messages (BSMs) every tenth of a second.

Cooperative environment for vehicles helps reduce stress and unsafe close interaction with other vehicles while facilitating good synchronization of observations (Ntousakis, Nikolos, & Papageorgiou, 2016). Cooperative Merging (CM) which is also referred to as Cooperative Merging Assist (CMA), assist the driver in lane changing maneuvers by creating and maintaining an appropriate gap in the target lane (Tampere, Hogema, Katwijk, & Van Hem, 1999).

Microscopic Traffic Simulation

The effectiveness of certain traffic control strategies can be tested by simulation experiments which mimic real traffic conditions (Sarvi et al., 2004). One of the important tools for management and analysis of a transport system is Microscopic traffic simulation models which assist Traffic Engineers (Hidas, 2002). Microscopic simulations help in the study and evaluation of transport network systems performance under different scenarios such as incidents which can result in spatial temporal capacity reduction and thus cause congestion in the network. Capacity of a facility such as the freeway, can be defined as the maximum hourly rate at which vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions (Transportation Research Board, 2000).

Microscopic Simulation on Merging Maneuver

In simulation of freeway merging maneuver, the essential components of all microscopic simulation models are the oscillation (acceleration-deceleration) characteristics of merging vehicles in the acceleration lane (Sarvi et al., 2004). The analysis of merging bottlenecks and designing of the control strategies and optimum geometry for merging areas can be performed by the use of microscopic simulation (Choudhury et al., 2009).

Microscopic Simulation Models for Merging Maneuver

Gap acceptance model combined with car following algorithm represents a classical way to represent the interactions of vehicle at merges at the microscopic level (Kolen, 2013). Microscopic traffic simulation models consist of several sub-models that are used to describe driving behavior (Fransson, 2018). These sub-models have great influence in obtaining accurate results. It is claimed that, car-following and lane changing models are the key components. Among others, the lane change behavior of vehicles apart from being complex is also a fundamental part of microscopic traffic flow simulation model (Wan et al., 2014).

Based on the car following algorithm which simulates vehicle trajectories on minor roads as well as on major roads, and also based on the insertion decision model which specifies whether the demand for insertion could be met according to traffic conditions upstream and downstream of the conflict point, the challenges and uncertainties involved during merging maneuvers can be captured by microscopic frameworks (Chevallier & Leclercq, 2009). For low flows and conventional highway speeds, a microscopic simulation model for automated merging section indicates that, with or without fixed-time ramp metering a two-lane conventional freeway has similar characteristics like a one lane automated highway systems (AHS) merging section having an exclusive entrance ramp (Ran et al., 1999). The difference is observed when there is a break down in conventional freeway whereby the AHS continues to perform with observable little delay.

Microscopic Simulation for Aging Drivers

Microscopic simulation shows that, senior drivers merge at low speed and create turbulent traffic situation at the merging point (Immers et al., 2015). Sometimes the older driver may come to standstill on acceleration lane and create queue on the ramp.

Instrumented Vehicles (IV) Under Natural Settings

Drivers' performance and safety of traffic have attracted attention from many researchers who have utilized the use of instrumented vehicles to study a variety of drivers' behavior in different traffic conditions on different locations of the roadway including the merging locations on freeways. In an instrumented vehicle experiment, participants performed many merging maneuvers during uncongested conditions compared to congested conditions (Kondyli & Elefteriadou, 2009). The majority of merging maneuvers during uncongested condition were free maneuvers and participants entering freeway received cooperation through deceleration rather than lane changing. Interestingly, participants on the freeway showed cooperation more through lane changing compared to decelerating, and they were involved in free and cooperative maneuvers and not forced merges.

Under Paced Auditory Serial Addition Task (PASAT) in an instrumented vehicle, an experiment administered on a relatively straight freeway segment during the day under good weather (sunny day) and traffic conditions (no traffic jam), aged drivers were observed to commit numerous at-faulty safeties errors compared to young drivers (Thompson et al., 2012). Though under the stated scenario of driving conditions on the freeway, the process is observed to be more automated especially for experienced drivers. Despite the fact that elderly drivers adopt more conservative vehicle control strategy in multiple target identification under normal freeway conditions, they exhibit worse driving performance in comparison with other age groups (Zahabi et al., 2017). Posing a high workload to aging drivers, when driving, might result in incorrect responses or even lead to old driver missing important driving-related signage and hence being prone to crashes (Natasha, Anttila, & Luoma, 2005). To avoid any adverse impact due to shared information in dynamic environment older drivers must be provided with a well-designed means of relaying that information.

Driving Simulator for Aging Drivers

Driving Simulator Overview

The simulator-based experiments can mimic the real driving experience for drivers in different driving conditions (Shi & Liu, 2019). The surrounding environment, the vehicle interactions and other road features can be modeled during the experiment though the verification of results from real road data is important. Regardless of weather and time of the day, the driving simulator can be used for simulation of various traffic situations and thus avoid risk to the drivers and other road users for the same situations in real traffic (Karthaus & Falkenstein, 2016). Furthermore, in the driving simulator, there are possibilities of repeating and controlling the critical situations since the driving simulator can be programmed. During driving simulator experiments, the participants especially older drivers can get simulator sickness in most of "out-of-car" set ups (Brooks et al., 2010). This draws attention on the need for a careful assessment of participants and the results of the simulation.

Experiments of Driving Behavior in Driving Simulator

In identifying older drivers' risk of motor vehicle crashes, an experiment which utilized a driving simulator identified cognitive skills, such as working memory, concentrating, reaction times and decision making are associated with crash events (H. C. Lee, Lee, Cameron, & Li-Tsang, 2003). Furthermore, the odds of a crash occurrence increase due to presence of deficiencies on these skills with an inability to make rapid decisions and judgement.

In another investigation conducted on a driving simulator, a cross-sectional study investigated the links between mental workload, age and risky driving and identified the moderate scenario complexity to be the best in noting the differences in driving ability between drivers in naturalistic driving behavior based on driver's age (Michaels et al., 2017). In this experiment, without external pressure (moderate scenario complexity), inexperienced younger and the experienced adult participants drove at a significant higher speed compared to older participants.

At Chungnam Techno Park (CTP), Korea Automobile Technology Institute, a driving simulator experiment involving young drivers (26.3±2.0 years) and elderly drivers (65.6±5.0 years), was conducted and the results showed that the elderly drivers have poor driving performance compared to young drivers (Park, Min, Lee, & Subramaniyam, 2015)**.** All participants in the experiment had no health problems associated with the mind or visibility (eye positions details were collected by the faceLAB eye-tracking system) to drive a car in the driving simulator and the elderly drivers had an experience of 32.5±9.4 years compared to young drivers with experience of 3 years. Furthermore, simulation sickness was observed to affect elderly drivers compared to young drivers who showed mild to moderate discomfort for the sickness.

Elderly drivers' behavior to hazardous traffic maneuvers differ from younger drivers' behavior. The cognitive capacity of elderly drivers is sought to have an impact on the identification of hazard and making proper response like braking as they were observed to brake ahead of where they really needed to. Moreover, older drivers were slower to fixate on hazardous stimuli, but also demonstrated a wider visual scanning pattern compared to younger drivers. Interestingly, the older drivers show the ability to divide the time across areas of the environment while driving than younger drivers could divide the time to look both inside the car (speedometer) and outside the vehicle.

Literature Review Summary

Aging has impacts on driver's ability to react and make correct decisions when driving. The diminishing capabilities on vision, physical strength and cognition are experienced more when the driver is subjected to a more complex maneuver. There are situations that demand simultaneous or quick succession reactions from the driver of which is a big challenge to elderly drivers. These situations are associated with risks not only to older drivers, but also to other road users. The difficulties of these older drivers can be determined through field observations, collecting data from instrumented vehicles or the use of driving simulator which mimic the actual driving environments.

Freeway merging maneuver is one of the challenging areas that old drivers have difficulties. Even though senior drivers avoid driving in hard conditions such as peak hours of the day or in bad weather, they are still observed to have difficulties in freeway merging areas. In merging areas, where there is an acceleration lane, aging drivers do merge with slow speed compared to other young and middle-aged drivers, but they also do merge near the end of the acceleration lane. The former situation poses significant interactions to the mainline traffic as the approaching vehicle in the mainline to the merging area will need to decelerate so as to create gap for a merging vehicle and this results in a shock wave in the traffic flow. The latter merging condition can result in the same perturbations in the mainline traffic but also there can be a traffic flow breakdown on the ramp.

The emerging technologies in intelligent transportation systems have potential in addressing the problems faced by aging drivers during the freeway merging maneuver. Using wireless connectivity, the vehicles can cooperate with each other or the infrastructure and share information that can lead to proper actions from the drivers approaching or in the merging area.

The connected vehicles technology provide means for vehicles to share information such as positions and speed and the driver's decision is enhanced by the information received regarding the other vehicles.

Sensitivity analysis can be carried out using microsimulation tools to evaluate the potentials of connected vehicles technology in enhancing aging drivers merging maneuvers. Thus, merging control algorithm in Cooperate merging assistance system can be developed and evaluated to determine its ability in improving safety and traffic operations in freeway merging areas. Since elderly drivers are more challenged in driving operations, having a means to aid their driving capabilities it means that all drivers capabilities can be enhanced.

CHAPTER 3 METHODOLOGY

Model Building

Two base models were created in a previous study that modeled older drivers' behavior on freeway merging. The study created base models after collecting geometric characteristics, traffic volumes, vehicle speed, vehicle trajectories, and drivers' age and then compared observed field and simulation results. Two models of the study site locations were created in Vissim. PTV America defines Vissim as a microscopic, time step, and behavior-based simulation model developed at the University of Karlsruhe, Germany in 1992 and launched in 1993. The coding guidelines used are provided in Traffic Analysis Handbook (Florida Department of Transportation, 2014). The calibrated parameters are provided in this study and more details on the calibration and validation on the models can be obtained in (Lwambagaza, 2016).

Site Locations

Two site locations were selected for this study. The sites are identical 6-lane divided highway sections along I-75 in Lee County, Fort Myers, Florida. The mainline (I-75) at each site consists of three 12ft lanes. The acceleration lane for the on-ramp at the Pine Ridge road has a length of 1500 feet, which is longer than that of the Corkscrew road on-ramp (approximately 1000 feet). Both acceleration lanes have a standard width of 12ft. The selection of these sites was based on the presence of base models developed in a previous study (Lwambagaza, 2016), and the high percentage of older population within the County. The population aged 65 and over is expected to be more than 27% in Florida, overall, of by the year 2030 (Safety Mobility for Life Coalition, 2018), and Lee county currently has an older population of approximately 25.2% (BEBR, 2017). Figure 3.1 shows the location and characteristics of the two study sites.

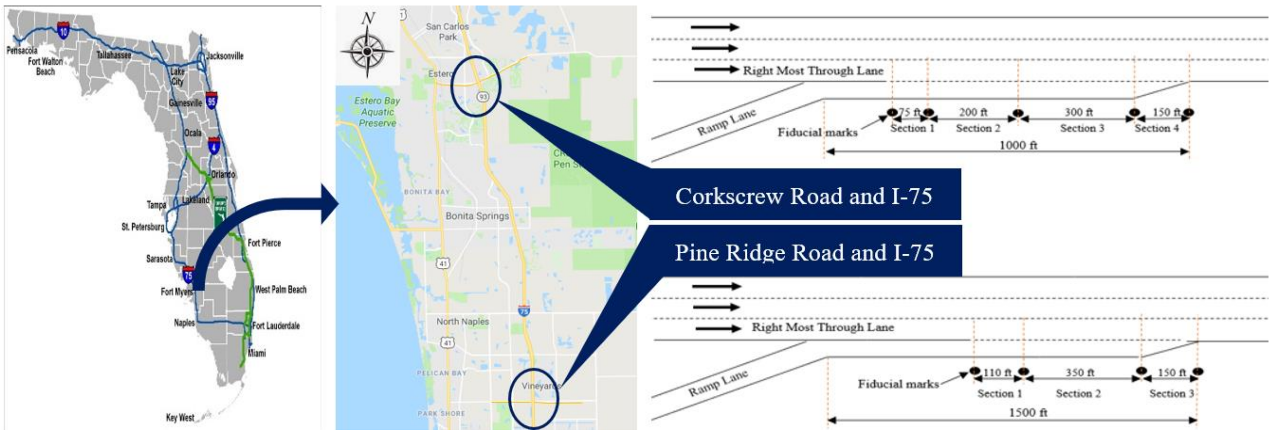


Figure 3.1: Map and Schematic of I-75 On-Ramps at Corkscrew Road and Pine Ridge Road (Source: Google Earth, 2019) (Not to scale)

Calibration Parameters

The 2016 study on older driver behavior related to freeway merging (Lwambagaza, 2016) collected geometric characteristics, speed of vehicles, traffic volumes, vehicle trajectories, and age of drivers on the study sites used in this study. Vissim microsimulation software was used to create the base models for the two site locations. The models were calibrated by changing two car-following parameters: the CC0 (standstill distance) and the CC1 (following distance/headway time). The calibration parameters, which reflect driver behavior observed during data collection at sites, are listed in Table 3.1.

Table 3.1: Site Models Adjusted Calibration Parameters (Lwambagaza, 2016)

Calibrated Parameters	**D**	**E**	**M**	**Y**	**F**
CC0 (ft)	4.92	4.9	3.0	3.0	4.9
CC1 (sec)	0.9	3.0	0.5	0.3	0.5

CCO: Standstill distance, CC1: Following distance/Headway time, D: Default values, E: Elderly, M: Middle, Y: Young Driver, and F: Freeway traffic

The CCO and CCI are defined by PTV (PTV, 2018) as follows;

CCO - Standstill distance: The desired stand still distance between two vehicles.

CC1 - Following distance (Headway time): Time distribution of speed-dependent part of the desired safety distance.

Network Coding

This study made use of Vissim version 11.0 which has more features than Vissim version 8.0 which was used to create the base models. Few adjustments were made on the base models before introducing the connected vehicles. PTV 2018 Manual provides instructions on modeling the merging area which is the main part of the models in this study. At the merging section, the number of lanes include the number of lanes on main link for mainline traffic and the number of merging lane(s) (acceleration lane). After the merging section, only one connector was used to the main link. For a realistic graphical representation, a dummy link was added at the end of the merging lane. The route for through traffic was coded so as not to allow the mainline traffic to enter the acceleration lane, and the routes for merging traffic was extended beyond the merging area. Figures 3.2 and 3.3 show the Vissim models that were used in this study.

Figure 3.2: Vissim Model for I-75 at Corkscrew Road

Figure 3.3: Vissim Model for I-75 at Pine Ridge Road

Development of Merging Algorithm

The initial development of cooperative merging algorithm was done in a previous study by (Mjogolo, Njobelo, Lwambagaza, & Sando, 2018). This study utilized the initial efforts of a previous study (Mjogolo et al., 2018) and completed the development of cooperative merging algorithm which involves five major steps: data collection, actions upon arrival at merging point, selection of gaps, safety requirements, and appropriate action(s) during merging.

Data Collection

The vehicle attributes that are collected from mainline vehicles are Veh ID, Link ID, Lane Number, Location, Speed, Desired Speed, Acceleration, Headway, Coordinate Front, and Vehicle type. These attributes are used to create the Basic Safety Messages (BSM). The BSM are sent by on-ramp vehicles to mainline vehicles (connected vehicles) within the communication range. In Vissim, the mainline vehicles that are in range are defined based on Dedicated Short-Range Communication (DSRC) as stated by (Kenney, 2011). In this study, mainline traffic in range are considered as those vehicles within 1500ft on the upstream of the merging area as suggested in *Highway Capacity Manual* (Transportation Research Board, 2000).

Arrival at Merging Point

Time to reach a fixed chosen merging point was calculated based on the current speed, acceleration and position of an on-ramp vehicle and each of the mainline vehicles in the Lane 1 (outer lane of mainline traffic).

Vehicle Selection for Creating Gaps

Time difference to reach a merging point between the mainline vehicle on lane 1 and the merging vehicle was determined. All the mainline vehicles with less or equal to $\pm 3s$ time differences were selected and the one with the smallest absolute time difference was considered as the starting point for adjusting speed. If the sign was negative the vehicle reached to the merging point before the on-ramp vehicle and so it was called leading vehicle and the opposite was the lagging vehicle. $\pm 3s$ was used because the recommended minimum safety following distance is 3 seconds.

Most drivers are used to a three-second rule in determining if they are following too close or at an appropriate gap. The National Safety Council recommends the same value of 3 seconds as the minimum following distance. Furthermore, different studies (Houchin, 2015; Wu & Liu, 2013) on gap acceptance found the acceptable gap ranges from 2 seconds to 3.1 seconds, although (Wu & Liu, 2013) found the mean to be around 1.22 seconds. Furthermore, a standard of 2.5 seconds is normally used by highway engineers in representing how long the driver takes to perceive, realize and react to hazards. Thus, a threshold of $\pm 3s$ is a correct value for safety gap creation.

Safety Requirements

In checking safety requirements, the first check involved leading or lagging vehicle and the on-ramp vehicle. Predicted headway between the two vehicles at the point of merging was determined and compared with the minimum safety distance requirement (MSDR) as stated in

PTV VISSIM Manual 2018. The second check involved mainline vehicles on lane 1. In case of leading vehicle, headways of all the front vehicles, including itself, were determined and compared with the MSDR. Same check was done for all the vehicles behind the lagging vehicles.

Appropriate Action

Based on the safety requirements results, the driver of the mainline vehicles on lane 1 choose to do nothing, accelerate/decelerate or change lane to the left lane. The actions were not ranked and hence the driver chose the best action(s) based on the pre-set conditions as explained below:

Do nothing; There were two conditions set for a driver to decide to do nothing: First; if the predicted headway between the leading/lagging vehicle and on ramp vehicle met MSDR, the vehicle chose to do nothing because of enough gap when the on-ramp vehicle reaches the merging point. Second; if the vehicle must adjust speed beyond the minimum or maximum allowable speed limit and it's not safe to change lane to the left lane. In this case a driver ignores a speed advisory of 20mph below the current driving speed and greater than 5mph above the posted speed limit.

Accelerating the leading vehicle only; A driver of the leading vehicle chose to accelerate if the predicted headway between the on-ramp and the leading vehicle didn't meet the MSDR, and the headways of the vehicles in front of the leading vehicle met MSDR.

Decelerating the lagging vehicle only; A driver of the lagging vehicle chose to decelerate if the predicted headway between the on-ramp and the lagging vehicle didn't meet the MSDR, and the headways of the vehicles behind the leading vehicle met MSDR.

Accelerating both the leading vehicle and vehicles in-front of it; If the predicted headway between the leading vehicle and the on-ramp vehicle didn't meet MSDR, and the headways of the front vehicles were smaller than MSDR, all vehicles in-front of the leading vehicle, including the leading vehicle accelerate.

Decelerating the lagging vehicles and vehicles behind it; If the predicted headway between the lagging vehicle and the on-ramp vehicle didn't meet MSDR, and the headways of vehicles behind the lagging vehicle were smaller than MSDR, the lagging vehicle and vehicles behind decelerate.

Changing Lane to The Left Lane

A driver on the mainline lane chose to change lane to the left lane if it is not safe to either accelerate or decelerate and safety condition for the vehicle to move to the left lane is satisfied.

Figure 3.4 shows the above-mentioned steps in a developed algorithm for a cooperative merging assistance system (CMAS) that helps to enhance older drivers' freeway merging maneuver.

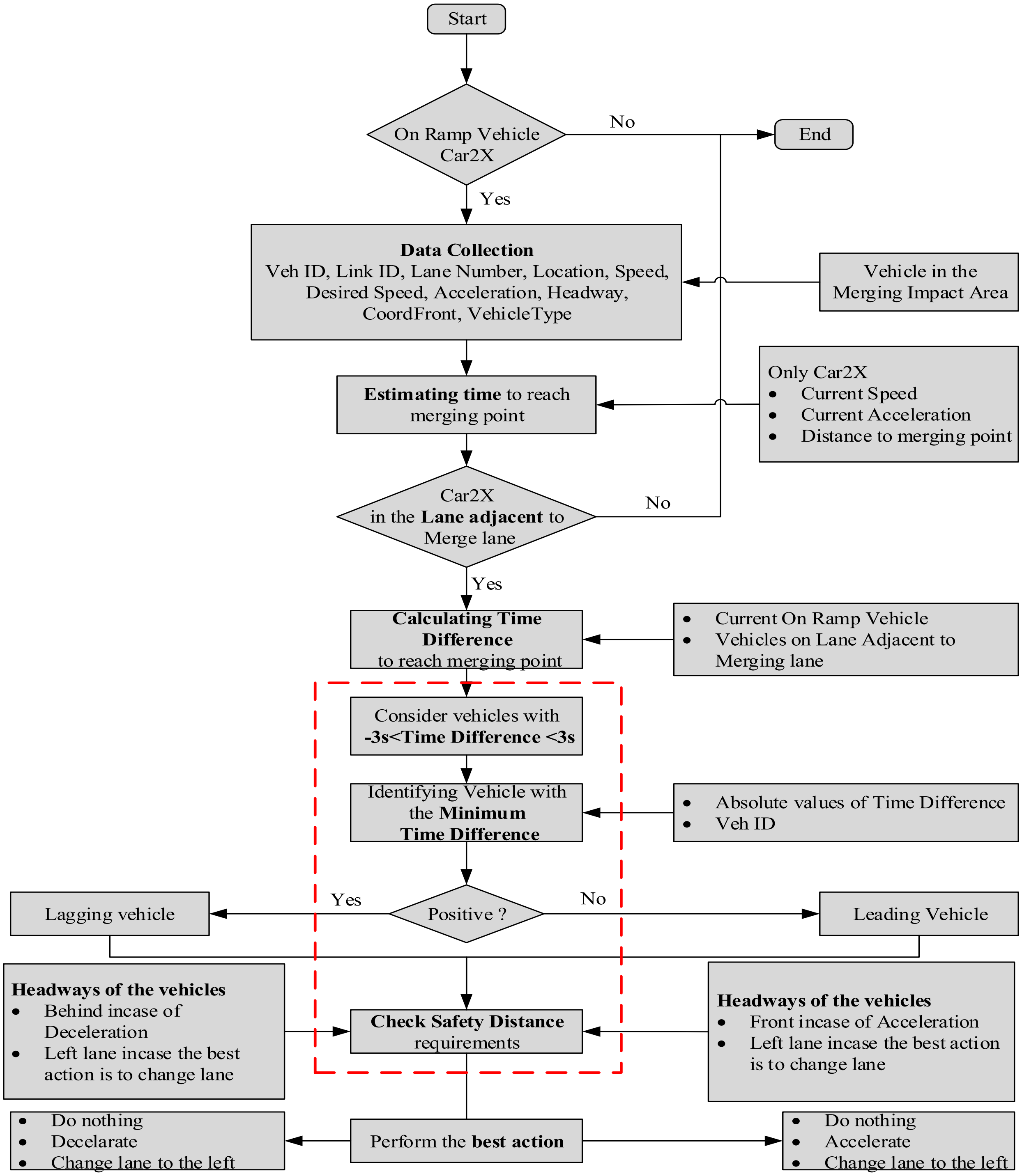


Figure 3.4: Logic Flow Chart of the CMAS Algorithm

Measures of Effectiveness

In this study, the focus was on three measures of effectiveness (MOEs): Merging Location, Merging Speed and Vehicle Interaction States (VISs) together with the rate of deceleration (hard braking) for aging on-ramp drivers.

Merging Location and Merging Speed

These MOEs were selected to evaluate the potential of CMAS in enhancing mobility of the aging on-ramp drivers. The aging on-ramp drivers have difficulties in accepting gaps which leads to utilization of the whole length of acceleration lane. With the traffic control strategy, the gaps in the mainline traffic are sought to be created earlier before the on-ramp vehicles stops at the end of acceleration lane

Vehicle Interaction States

This MOE was selected to evaluate the potential of CMAS in enhancing safety of the aging on-ramp drivers. The operations of a vehicle in the acceleration lane before merging depends on other vehicles in the acceleration and mainline traffic. The vehicle in the mainline might need to reduce speed to allow vehicle from the acceleration lane to merge. But also, the merging vehicle might need to apply brakes before changing lanes after failing to merge and sometimes might end up stopping near or at the end of acceleration lane if the gap to merge was not available. All braking scenarios might lead to higher rate of deceleration (hard braking) depending on the traffic conditions and operations. These interactions of vehicles in merging area have influence on safety performance of the facility.

Sensitivity Analysis

In this study, the connected vehicle environment was created in Vissim through the Component Object Model (COM) interface, whereby V2I (Vehicle-to-Infrastructure) and V2V (Vehicle-to-Vehicle) wireless communication between connected vehicles were modeled using the

Car2x (Car-to-Anything) Application Programming Interface (API). This type of connected vehicle modeling was completed for both study site Vissim models.

A total of 105 scenarios were evaluated. Since CV technology is not fully integrated, varying connected vehicle penetration rates of 0%, 20%, 40%, 50%, 60%, 80% to 100% were examined for mainline traffic, with all on-ramp vehicles having the capability of CV technology at each penetration rate. The composition of aging on-ramp drivers was based on the increase in aging population and the percentage of aging drivers during data collection and consisted of 10% to 50% in 10% increments at LOSs A, B and C. These LOSs were selected based on previous findings that older drivers avoid peak hours (Bruff & Evans, 1999), hence LOS A, B and C are conditions likely to be preferred by older drivers. This reason is also supported by the information gathered during field observations (Lwambagaza, 2016). Vehicle inputs into Vissim for the LOSs were derived from the highway capacity exhibits for freeways in the *Highway Capacity Manual* (Transportation Research Board, 2016) as shown in figure 3.5.

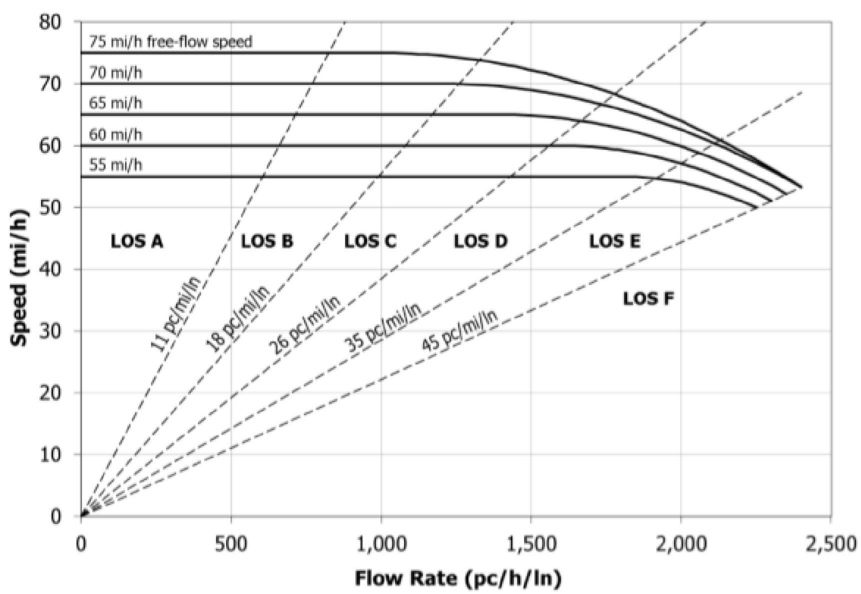


Figure 3.5: LOS Criteria and Speed-Flow Curves for Basic Freeway Segements (Source: Highway Capacity Manual, 2016)

Statistical Analysis

The statistical analysis used in this study are described in this section. The choice of statistical analysis depended on the measure of effectiveness. Confidence levels chosen for all MOEs, merging location, merging speed and vehicle interaction states was 95%. For Merging location, the intent was to compare the proportions from two samples and the null hypothesis stated that, proportions of late merges are the same with or without CMAS. The paired sample *z*-test which is a statistical procedure normally used to determine whether the mean difference between two sets of observations is zero was used for merging speed MOE. The Mann-Kendall trend test was used for vehicle interaction states. The reason of using Mann-Kendall was to statistically analyze the trend of vehicle interaction states with the increase in market penetration rate (MPR) of connected vehicles. Although Mann-Kendall is a time series test, it was adopted since the MPR for connected vehicles is proportional to time.

CHAPTER 4 MERGING LOCATION AND SPEED FOR AGING DRIVERS

Introduction

A merging maneuver can be defined as the operation of merging from an entry lane onto the mainline between two vehicles in a platoon (Yun-Lu & Hedrick, 2000). At merging areas, vehicles entering the freeway from on-ramps must compete for space to merge with mainline traffic by finding acceptable gaps in the traffic stream (Mergia et al., 2013; Transportation Research Board, 2000). Vehicles on the mainline generally travel at higher speeds, depending on the posted speed limit, making finding acceptable gaps and performing merging maneuvers more challenging for older drivers.

The length of the acceleration lane also influences driver decisions when entering a freeway. Unlike shorter acceleration lanes, longer acceleration lanes provide enough distance for vehicles to accelerate to mainline traffic speeds prior to joining the traffic stream. Drivers on shorter acceleration lanes may reach the end of the lane before an acceptable gap is available to merge onto the mainline, and thus, may be forced to stop at the end of the lane. However, Intelligent Transportation Systems (ITS) can be used as countermeasures to mitigate the challenges posed by shorter acceleration lanes.

Previous studies (Mjogolo et al., 2018; Radu Popescu-Zeletin & Rigani, 2010; Scarinci et al., 2017, 2015) developed and analyzed CMA systems. However, none of the studies evaluated the effect of acceleration lane lengths on the merging behaviors of aging drivers in a connected vehicle environment. A study by (Mjogolo et al., 2018) used a microsimulation approach to analyze the impacts of CV technology on merging behavior at freeway on-ramps with long acceleration lanes based on driver's age . The longer acceleration lane was observed to enhance the merging maneuver of aging drivers.

Merging Location

Aging drivers are observed to merge late during freeway merging maneuver. As explained earlier, this is due to the challenges they have which makes it difficult to perform complex operations on roadways. The CMAS is designed in such a way that the gaps in the outer most lane of the freeway are created earlier whenever there is a presence of on-ramp vehicle. These gaps are either created by a deceleration, acceleration or lane change of the vehicles in the mainline. A do nothing is also an option depending on limitations such as minimum or maximum speed limit and presence of the gap for lane change.

In this study, the merging locations were divided into 4 sections at Corkscrew entrance and 3 sections for Pine Ridge entrance, Figures 4.1 and 4.2. From vehicle records files, the distance from the start of the merging point to the merging location of each modeled aging driver was identified in each scenario.

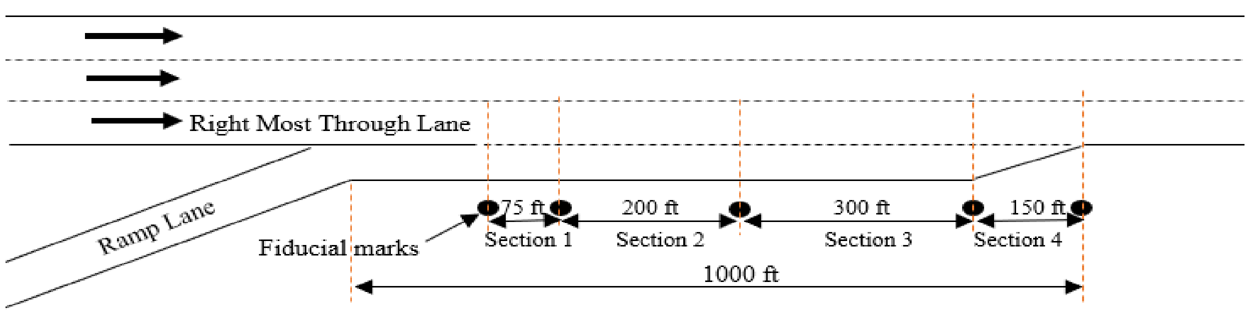


Figure 4.1: On-Ramp Geometry for I-75 at Corkscrew Road (Not to Scale)

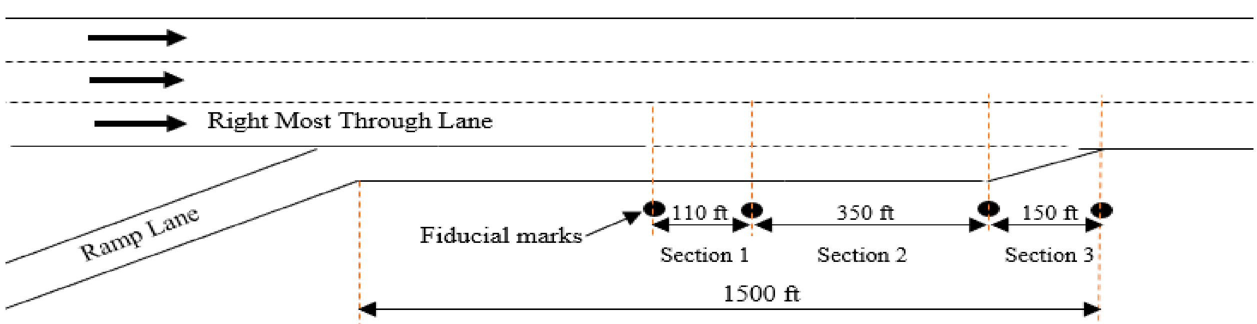


Figure 4.2: On-Ramp Geometry for I-75 at Pine Ridge Road (Not to Scale)

Merging Speed

The speed travelled by vehicles in the mainline might be challenging to the on-ramp vehicles. It is difficult for an on-ramp vehicle travelling at 40 mph to merge into a freeway with traffic moving at 60 mph. Either the mainline traffic decreases speed, which is a rare scenario, or an on-ramp vehicle increases speed, a desired scenario. CMAS allows the deceleration and acceleration of the vehicles in the mainline so as to allow the on-ramp vehicle to merge.

To accelerate and catch up with speed of mainline traffic, the on-ramp vehicle needs to accelerate in the acceleration lane before merging. But the issue is always not the vehicle speed, sometimes the traffic flow may be moving with low speed around 40 mph, but the gaps are not large enough to allow merging. Thus, freeway merging maneuver is the operation that involve simultaneous and/or quick succession actions for safe and efficient traffic operations.

Results and Discussions on Sensitivity Analysis

Results

Figures 4.3 illustrate the merging patterns for different composition rates of aging on-ramp drivers with (W) and without (W/O) CMAS for mainline LOSs A, B, and C at the two study sites. The more detailed information on variations in percentage of merges for different CV penetrations and aging drivers' composition are shown in Appendix 1 to 6 for both study areas.

Figures 4.4 and Table 4.1 show the average merging speed of aging on-ramp drivers at different composition rates of aging on-ramp drivers when CMAS was employed (100% CV adoption rate) for LOS A, B, and C. The more detailed information on variations of average merging speed for different CV penetrations and aging drivers' composition are shown in Appendix 7 to 12 for both study areas.

Figure 4.3: Merging Patterns of Aging On-Ramp Drivers (with and without CMAS)

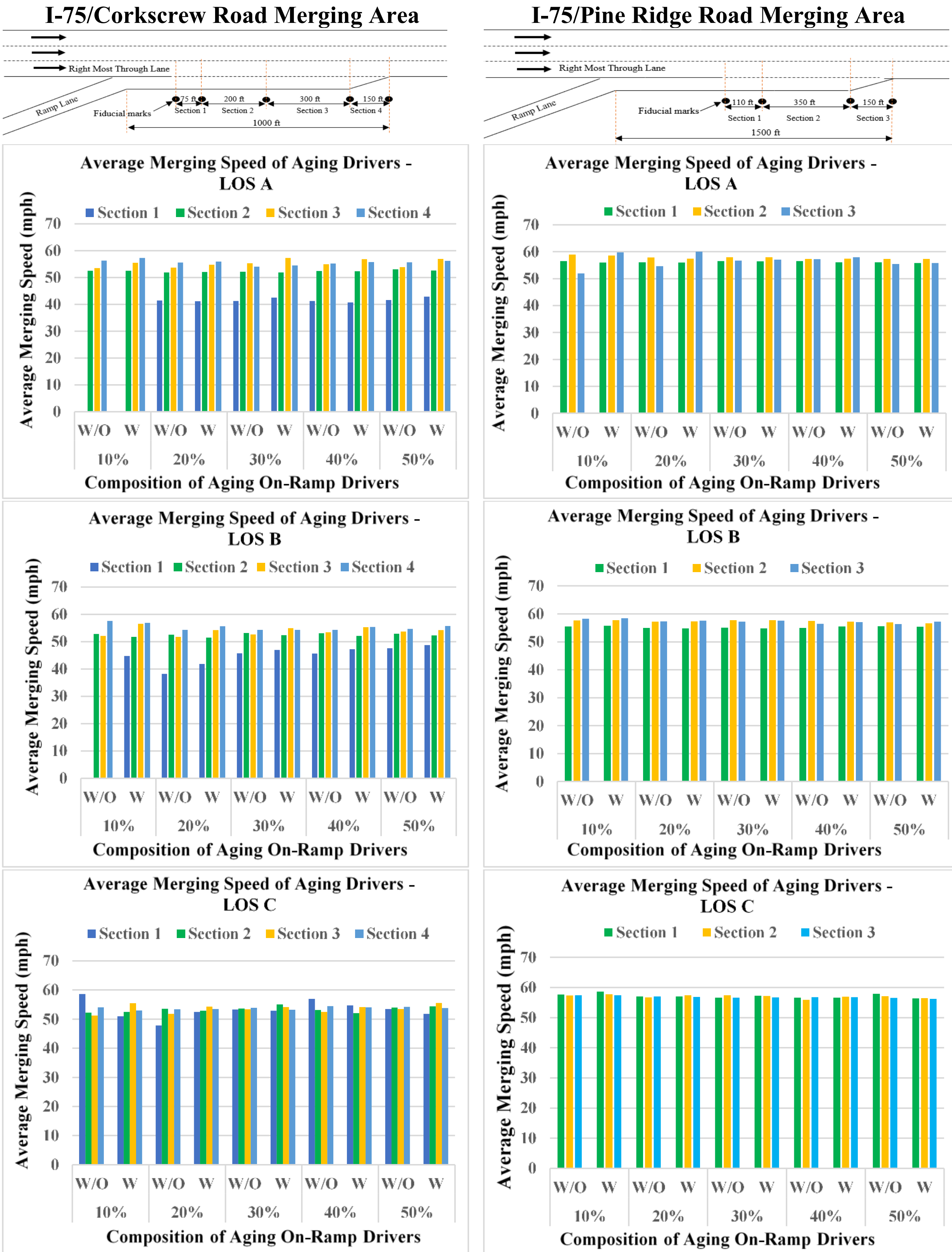


Figure 4.4: Average Merging Speed of Aging On-Ramp Drivers (with and without CMAS)

Table 4.1: Average Merging Speed of Aging On-Ramp Drivers

Composition of Aging On-Ramp Drivers	Mainline Traffic Environment	Shorter Acceleration Lane					Longer Acceleration Lane		
		Average Merging Speed (mph) of Aging On-Ramp Drivers at LOS A							
		Section 1	Section 2	Section 3	Section 4		Section 1	Section 2	Section 3
10%	Without CMAS		52.5	53.5	56.3		56.5	59.0	51.9
	With CMAS		52.5	55.5	57.3		56.0	58.6	59.8
20%	Without CMAS	41.4	51.9	53.7	55.6		56.1	57.9	54.7
	With CMAS	41.1	52.1	54.8	55.9		56.0	57.5	60.0
30%	Without CMAS	41.2	52.1	55.3	54.1		56.5	58.0	56.7
	With CMAS	42.5	51.9	57.3	54.5		56.5	57.9	57.1
40%	Without CMAS	41.2	52.4	55.0	55.2		56.5	57.4	57.3
	With CMAS	40.7	52.3	56.9	55.8		56.1	57.5	58.0
50%	Without CMAS	41.6	53.1	53.8	55.6		56.1	57.4	55.5
	With CMAS	42.9	52.6	56.9	56.2		55.8	57.4	55.8
		Average Merging Speed (mph) of Aging On-Ramp Drivers at LOS B							
10%	Without CMAS		52.8	52.1	57.6		55.5	57.6	58.3
	With CMAS	44.8	51.8	56.6	56.9		55.8	57.8	58.5
20%	Without CMAS	38.2	52.6	51.8	54.4		54.9	57.2	57.3
	With CMAS	41.9	51.5	54.3	55.7		54.8	57.3	57.6
30%	Without CMAS	45.7	53.1	52.7	54.3		55.0	57.7	57.2
	With CMAS	47.0	52.4	55.0	54.3		54.9	57.8	57.6
40%	Without CMAS	45.6	53.1	53.4	54.4		55.0	57.5	56.5
	With CMAS	47.3	52.1	55.3	55.4		55.5	57.2	57.1
50%	Without CMAS	47.6	53.0	53.8	54.7		55.6	57.0	56.4
	With CMAS	48.7	52.3	54.2	55.8		55.4	56.7	57.3
		Average Merging Speed (mph) of Aging On-Ramp Drivers at LOS C							
10%	Without CMAS	58.6	52.2	51.2	54.0		57.7	57.4	57.4
	With CMAS	51.0	52.4	55.5	52.9		58.7	57.8	57.4
20%	Without CMAS	47.8	53.5	51.8	53.3		57.1	56.8	57.1
	With CMAS	52.5	52.9	54.3	53.5		57.0	57.4	56.9
30%	Without CMAS	53.3	53.7	53.3	53.9		56.7	57.4	56.7
	With CMAS	52.9	55.1	54.1	53.2		57.3	57.2	56.7
40%	Without CMAS	56.9	53.2	52.5	54.4		56.7	55.9	56.8
	With CMAS	54.7	52.0	54.1	54.1		56.7	57.0	56.8
50%	Without CMAS	53.4	54.0	53.5	54.2		57.9	57.1	56.6
	With CMAS	51.8	54.3	55.5	53.8		56.4	56.5	56.2

Discussions

Merging location

The utilization of CMAS changes the merging location of aging drivers. The percentage of late merges (merging at the last section of the acceleration lane) decreased with CMAS since the vehicles in the mainline traffic provided enough gaps before the merging vehicle reached the end of acceleration lane. The rate of decrease in the percentage of merges differed between the two study sites. This observed difference can be attributed to the difference in acceleration lane length, the primary difference between the two sites.

Table 4.2 provides the percentage reduction in late merges for Corkscrew and Pine Ridge entrances between 0% of connected vehicles and with a 100% CV penetration rate, i.e., when all vehicles in the mainline and on-ramp are connected vehicles.

Table 4.2: Percentage Reduction in Late Merges

LOS	Composition of Aging On-Ramp Drivers	Percentage Reduction in Late Merges (100% CV)	
		Longer Acceleration Lane	Shorter Acceleration Lane
A	10%	60.0%	60.0%
	20%	60.0%	32.0%
	30%	10.0%	41.2%
	40%	23.8%	35.4%
	50%	41.7%	24.1%
B	10%	38.1%	22.2%
	20%	26.9%	17.6%
	30%	24.9%	15.7%
	40%	13.2%	5.8%
	50%	19.8%	-1.0%
C	10%	16.6%	21.6%
	20%	9.5%	15.1%
	30%	14.3%	11.9%
	40%	10.0%	10.3%
	50%	7.6%	14.9%

For both entrances, the percentage of late merges with CMAS was lower compared to merging without CMAS. For the same conditions of traffic demand and composition of older drivers, there was a greater reduction in late merges on the longer acceleration lane (Pine Ridge) when CMAS was employed, compared to the shorter acceleration lane (Corkscrew). At the longer acceleration lane, the percentage reductions were 60.0%, 38.1%, and 16.6%, while at the shorter acceleration lane the percentage reductions were 60.0%, 22.2%, and 21.6% when the composition of aging on-ramp drivers was 10% for LOS A, B, and C, respectively. When the composition of aging on-ramp drivers increased to 50%, the percentage reductions were 41.7%, 19.8%, and 7.6% at the longer acceleration lane, while at the shorter acceleration lane, the percentage reductions were 24.1%, and 14.9% for LOS A, and C, respectively but there is no any reduction for LOS B. Similar trends were observed for intermediate compositions of aging on-ramp drivers (at 20%, 30%, and 40%); however, some exceptions were observed with aging driver compositions for LOS A and LOS C.

Also, the percentage reduction decreased with an increase in traffic demand. At the longer acceleration lane, the percentage reductions were between 60.0% to 10.0% at LOS A, 38.1% to 13.2% at LOS B, and 16.6% to 7.6% at LOS C, with standard deviations of 22.2%, 9.2%, and 3.7% for LOS A, B, and C respectively. At the shorter acceleration lane, the percentage reductions were between 60.0% to 24.1% at LOS A, 22.2% to 5.8% at LOS B, and 21.6% to 10.3% at LOS C, with standard deviations of 13.5%, 9.4%, and 4.3% for LOS A, B, and C, respectively.

These findings support that at low traffic flow on the mainline (LOS A), there is ample freedom to easily merge with traffic; hence, mainline vehicles can more easily create gaps earlier in the merging area than when traffic demand is at a LOS B or C. This result can be attributed to the stochastic nature of traffic depicted in Vissim (PTV, 2018); however, the reduction in late merging is also dependent on length of the acceleration lane. Observations also indicate that the composition rate of aging drivers influence the reduction rates of late merges. The greater the composition of aging drivers, the smaller the reduction rate of late merges. Similarly, percentage reductions of late merges are higher at longer acceleration lanes than at shorter acceleration lanes.

Merging Speed

The average merging speed of aging drivers without connected vehicles does not significantly differ from the average merging speed of those with CVs when CMAS is utilized. Except for section 1 on the shorter acceleration lane, findings reveal that all aging drivers merge at nearly the same speed, with or without CMAS, at all merging sections and LOSs analyzed, regardless of aging on-ramp driver composition and acceleration lane length.

The analysis showed that older drivers tended to merge at lower speeds, around 40 mph, at section 1 of the shorter acceleration lane with or without CMAS, compared to merging at around 50 mph in section 1 at the longer acceleration lane with or without CMAS. This suggests that aging drivers were more comfortable merging at higher speeds when additional lane length is available. Generally, the average merging speeds of older drivers did not depend on the merging location (i.e., section of the acceleration lane). This finding is consistent with a previous study on aging drivers (Lwambagaza, 2016).

Results and Discussions on Statistical Analysis

Merging Speed

A z-test for merging speed was conducted with a null hypothesis stating that, the difference between the speed means is equal to zero tested against the alternative hypothesis that the difference between speed means is different from zero under 95% confidence level. The test was conducted for both site locations, for LOSs A, B, and C, for each analyzed composition of aging on-ramp drivers. The results indicated that the average merging speed of aging on-ramp drivers for any scenario with CMAS is the same as without CMAS. With 95% confidence level, the z-critical value is 1.960 and alpha is 0.05. Table 4.3a and 4.3b provide summary of the results from a *z*-test statistic.

Table 4.3a: Results of Paired Z-Test for Merging Speed (LOS A and B)

Composition of Aging On-ramp Drivers	**LOS A**					**LOS B**				
		Corkscrew entrance		**Pine Ridge entrance**			**Corkscrew entrance**		**Pine Ridge entrance**	
		Without CMAS	**With CMAS**	**Without CMAS**	**With CMAS**		**Without CMAS**	**With CMAS**	**Without CMAS**	**With CMAS**
10%	**N**	74	74	87	87	**N**	106	106	127	127
	Mean	53.252	53.252	57.832	57.845	**Mean**	53.491	53.491	57.200	57.212
	StDev	6.482	6.482	5.193	5.225	**StDev**	7.164	7.164	5.351	5.363
	z	0.000		-0.017		**z**	0.000		-0.018	
	p-value	1.000		0.986		**p-value**	1.000		0.986	
20%	**N**	154	154	155	155	**N**	236	237	239	241
	Mean	52.753	52.753	57.267	57.275	**Mean**	52.744	52.743	56.644	56.703
	StDev	7.288	7.288	5.267	5.286	**StDev**	7.759	7.742	5.393	5.391
	z	0.000		-0.013		**z**	0.001		-0.120	
	p-value	1.000		0.990		**p-value**	1.000		0.904	
30%	**N**	238	238	236	236	**N**	384	383	359	357
	Mean	52.753	52.753	57.499	57.498	**Mean**	53.193	53.185	56.961	56.985
	StDev	7.069	7.069	5.308	5.325	**StDev**	7.447	7.456	5.365	5.369
	z	0.000		0.001		**z**	0.015		-0.059	
	p-value	1.000		0.999		**p-value**	0.988		0.953	
40%	**N**	319	319	333	332	**N**	505	506	504	507
	Mean	53.170	53.170	57.147	57.145	**Mean**	53.368	53.354	56.704	56.713
	StDev	7.200	7.200	5.448	5.461	**StDev**	7.476	7.476	5.456	5.487
	z-value	0.000		0.005		**z-value**	0.030		-0.026	
	p-value	1.000		0.996		**p-value**	0.976		0.979	
50%	**N**	407	407	410	409	**N**	636	634	623	624
	Mean	53.370	53.370	56.867	56.867	**Mean**	53.461	53.441	56.477	56.485
	StDev	6.995	6.995	5.525	5.543	**StDev**	7.230	7.225	5.463	5.469
	z-value	0.000		-0.001		**z-value**	0.049		-0.027	
	p-value	1.000		0.999		**p-value**	0.961		0.979	

Table 4.3b: Results of Paired Z-Test for Merging Speed (LOS C)

Composition of Aging On-ramp drivers		LOS C			
		Corkscrew entrance		Pine Ridge entrance	
		Without CMAS	With CMAS	Without CMAS	With CMAS
10%	N	152	154	177	178
	Mean	53.368	53.368	57.417	57.507
	StDev	7.149	7.185	5.436	5.444
	z	-0.001		-0.156	
	p-value	1.000		0.876	
20%	N	346	340	336	340
	Mean	52.904	53.509	56.989	57.024
	StDev	7.660	7.046	5.336	5.314
	z	-1.077		-0.086	
	p-value	0.281		0.932	
30%	N	533	469	482	495
	Mean	53.703	53.495	56.841	56.868
	StDev	7.097	7.472	5.430	5.402
	z	0.451		-0.079	
	p-value	0.652		0.937	
40%	N	683	621	617	616
	Mean	53.936	53.902	56.583	56.834
	StDev	7.290	7.346	5.521	5.528
	z	0.084		-0.799	
	p-value	0.933		0.424	
50%	N	803	725	799	797
	Mean	54.007	53.946	56.873	56.390
	StDev	7.183	7.177	5.546	5.606
	z	0.166		1.727	
	p-value	0.868		0.084	

Note: N = Number of samples, mean: Average merging speed for aging on-ramp drivers: StDev: Standard deviation, z: Observed z-value

Merging Location

For Merging location, the intent was to compare the proportions from two samples of the late merges, with and without CMAS. A z-test for population proportions of late merges was conducted with a null hypothesis stating that, the difference between the population proportions for late merges is equal to zero, tested against the alternative hypothesis that the difference between population proportions for late merges is different from zero. The test was conducted for both site locations, for LOSs A, B, and C, for each analyzed composition of aging on-ramp drivers. With 95% confidence level, the z-critical value is 1.960 and alpha is 0.05. The results indicated that the population proportions for late merges of aging on-ramp drivers are not significantly different at any composition of aging on-ramp drivers for level of service B. For LOS A and C, a mixture of results for insignificant and significant differences between the late merges proportions was observed when CMAS was employed and when not employed. Table 4.4a and 4.4b provide summary of the results from a *z*-test for population proportions.

Table 4.4a: Z-test for Population Proportions Results for Late Merges (LOS A and B)

Composition of Aging On-ramp Drivers	LOS A					LOS B				
		Corkscrew entrance		Pine Ridge entrance			Corkscrew entrance		Pine Ridge entrance	
		Without CMAS	With CMAS	Without CMAS	With CMAS		Without CMAS	With CMAS	Without CMAS	With CMAS
10%	**Proportion**	0.135	0.054	0.057	0.023	**Proportion**	0.17	0.132	0.165	0.102
	N	74	74	87	87	**N**	106	106	127	127
	z -value	1.684		1.144		**z -value**	0.773		1.476	
	p-value	0.093		0.254		**p-value**	0.441		0.139	
		Not significant		Not significant			Not significant		Not significant	
20%	**Proportion**	0.162	0.11	0.065	0.026	**Proportion**	0.246	0.203	0.159	0.116
	N	154	154	155	155	**N**	236	237	239	245
	z -value	1.331		1.647		**z -value**	1.121		1.375	
	p-value	0.184		0.099		**p-value**	0.263		0.171	
		Not significant		Significant			Not significant		Not significant	
30%	**Proportion**	0.143	0.084	0.085	0.076	**Proportion**	0.229	0.193	0.198	0.148
	N	238	238	236	236	**N**	384	383	357	359
	z -value	2.029		0.359		**z -value**	1.223		1.769	
	p-value	0.042		0.719		**p-value**	0.222		0.077	
		Significant		Not significant			Not significant		Not significant	
40%	**Proportion**	0.15	0.097	0.075	0.057	**Proportion**	0.248	0.233	0.232	0.202
	N	319	319	333	333	**N**	505	506	504	506
	z -value	2.034		0.936		**z -value**	0.558		1.157	
	p-value	0.042		0.347		**p-value**	0.575		0.246	
		Significant		Not significant			Not significant		Not significant	
50%	**Proportion**	0.143	0.108	0.105	0.061	**Proportion**	0.25	0.252	0.212	0.17
	N	407	407	410	409	**N**	636	634	623	624
	z -value	1.507		2.282		**z -value**	-0.082		1.887	
	p-value	0.131		0.023		**p-value**	0.936		0.059	
		Not significant		Significant			Not significant		Not significant	

Table 4.4b: Z-test for Population Proportions Results for Late Merges (LOS C)

Composition of Aging On-ramp drivers	LOS C				
		Corkscrew entrance		Pine Ridge entrance	
		Without CMAS	With CMAS	Without CMAS	With CMAS
10%	Proportion	0.704	0.552	0.701	0.584
	N	152	154	177	178
	z -value	2.750		2.300	
	p-value	0.006		0.021	
		Significant		Significant	
20%	Proportion	0.714	0.606	0.705	0.638
	N	346	340	336	340
	z -value	2.987		1.854	
	p-value	0.003		0.064	
		Significant		Not significant	
30%	Proportion	0.702	0.618	0.71	0.608
	N	533	469	482	485
	z -value	2.806		3.345	
	p-value	0.005		0.0008	
		Significant		Significant	
40%	Proportion	0.707	0.634	0.721	0.649
	N	683	621	617	616
	z -value	2.805		2.721	
	p-value	0.005		0.007	
		Significant		Significant	
50%	Proportion	0.72	0.612	0.732	0.676
	N	803	725	739	732
	z -value	4.479		2.353	
	p-value	<0.00001		0.019	
		Significant		Significant	

Despite the statistical results in table 4.4a and 4.4b showing that there are is no significant difference for merging with and without CMAS, the graphs in figure 4.3 indicate that there is reduction on late merges whenever CMAS is employed. The statistical analysis was conducted at higher significant level (95%), and this could be the reason of insignificant differences as the proportion's reductions are of small values as shown in table 4.2.

CHAPTER 5 AGING DRIVERS' INTERACTION STATES

Introduction

Some areas on highways are associated with significant speed variations where drivers need to decelerate or accelerate at a higher rate. Freeway merging areas are among those areas which demand more attention from drivers, and the required operations are prone to safety issues. At merging areas, vehicles entering a freeway from entrance ramps must compete for space with mainline traffic to find an acceptable gap to merge into the traffic stream (Mergia et al., 2013; Transportation Research Board, 2000). Finding suitable gaps during merging maneuvers is more challenging for older drivers. Oftentimes, they are forced to slow down in the acceleration lane and sometimes forced to stop when attempting to merge (Immers et al., 2015). Older drivers possess conservative behavior and generally do not force the merging maneuver. They may decelerate and wait until a large gap is presented (Kondyli & Elefteriadou, 2009); thus, creating a potential safety hazard.

Observed crash frequency or severity ranking criteria are several traditional methods currently being used in transportation network screenings (Agerholm & Lahrmann, 2012). These methods are subject to errors (Kockelman & Kweon, 2002), require considerable time for data collection (C. Lee, Hellinga, & Ozbay, 2006), and focus on observed crashes alone which are not complete predictors of safety (Stipancic, Miranda-moreno, Saunier, & Labbe, 2019). A good crash prevention measure is the result of investigating probable causes of crash events. Real-time crash prediction models and historical crash records are widely used in estimating crashes and their associated risks (Zhao & Lee, 2018), though perfect predictions of crashes cannot be made using only crash data (Stipancic, Miranda-Moreno, & Saunier, 2018).

In response to these challenges, surrogate safety measures (SSMs) have become a popular alternative to crash-based methods (Stipancic et al., 2019). These surrogate safety analyses include event-based techniques, behavioral techniques, and techniques based on measures of traffic flow (Stipancic et al., 2018). SSMs can be used to conduct safety analyses to assist in improving facilities and reducing safety issues (Stipancic et al., 2018).

The development and use of SSMs in safety analyses began in the 1960s. Post-encroachment time (PET), gap time (GT), and deceleration rate (DR) have been used for many years (Strauss, Zangenehpour, Miranda-Moreno, & Saunier, 2017), together with the most common SSM, Time to Collision (TTC). TTC is defined as the time required for two vehicles to collide if they continue at their present speeds and on the same path (Xie, Yang, Ozbay, & Yang, 2019). Apart from these surrogate measures, and also vehicle manouveres, more braking and accelerating may also be related to collision severity (Stipancic et al., 2018).

This study utilized Vissim as a microscopic simulation tool. Microscopic simulations can be used to estimate SSMs (Zhao & Lee, 2018). Oscillation (acceleration-deceleration) characteristics of merging vehicles in the acceleration lane are essential components in microscopic simulation models of freeway merging maneuvers (Sarvi et al., 2004). There are numerous SSMs specific to certain types of conflicts, and also missing validations of the measures (C. Wang & Stamatiadis, 2014). Although the Federal Highway Administration (FHWA) developed a Surrogate Safety Assessment Model (SSAM), none of the traditional surrogate safety measures are recommended (FHWA, 2008). In this study through the use of Vissim, which is a microscopic, time step, and behavior-based simulation model (PTV, 2018), vehicle operations were modeled and the interaction states identified and used as surrogate safety measures to evaluate the CMAS potential in enhancing safety for aging on-ramp drivers.

The interaction states of the vehicles in the freeway merging area can be used to predict the likelihood of crash occurrence during freeway merging. These interaction states provide insights on how vehicles maneuver in a certain area; they have thresholds which are defined as a combination of the difference in speed and position of vehicles on the roadway (Astarita, Festa, Giofrè, & Guido, 2019). The rate of deceleration (hard braking) threshold of 14.8ft/s^2 (AASHTO, 2011) can also be used to assess the likelihood of rear-end collisions.

Vehicle Interaction States

The vehicle interaction states (VISs) extracted from Vissim provide information on the operations of vehicles at different locations in the modeled freeway merging areas. PTV manual 2018 provides description of the interaction state attributes as outlined in Table 5.

Table 5: Description of Vehicle Interaction States in Vissim (PTV, 2018)

Interaction state	**Description**
Brake ZX	Target deceleration to an emergency stop distance for a lane change or a reduced speed area
Brake LC	Slight deceleration for a lane change in order to wait for the next upstream gap in the adjacent lane.
Brake cooperative	Cooperative braking to allow another vehicle to change lanes
Free	Vehicle is not affected by any relevant preceding vehicle. It tries to drive at desired speed, free driving
Follow	Vehicle tries to follow a leading vehicle at its speed
Brake BX	Braking at the desired safety distance (before reaching the safety distance), approaching
Brake AX	Braking at the desired safety distance (after reaching the safety distance)
Close up	The vehicle slowly closes in the following cases: • There is a stationary vehicle in front of it • While it is pulling out of a parking space in reverse onto its original link and upstream there is a stationary vehicle or a vehicle approaching • Until it reaches an obstacle, for example, a signal head, a stop sign, priority rule, conflict area.
External	Acceleration/deceleration is controlled by an external driver model DLL
Loss of attention	The parameter Temporary lack of attention is currently active, there is neither acceleration nor braking except for an emergency braking
Pass	Acceleration/deceleration to reach a permitted speed depending on the lateral distance for passing another vehicle in the same or an adjacent lane
Stop	The vehicle stops

The VISs for aging drivers and mainline traffic were extracted from the vehicle record files. For aging on-ramp drivers, the VISs used as surrogate measures were brake ZX (braking for emergency stop) and brake LC (braking for lane change), while brake cooperative was used for mainline traffic.

Brake ZX and Brake LC

When an on-ramp vehicle reaches an acceleration lane, it looks for the gaps available on mainline traffic. It is expected that the mainline traffic will be travelling at higher speed than the vehicle from ramp. Hence for a vehicle on the acceleration lane to merge properly, it must accelerate to catchup with the speed of the mainline traffic. During the merging process, several vehicles will be on the acceleration lane depending on the traffic demand. The vehicle on acceleration lane speeding more than other vehicles on the acceleration lane, if it won't have the gap in the right most through lane it will need to brake to avoid rear end collision while waiting for another gap. This braking scenario is what is referred to as Brake LC in the vehicle records files. The higher percentage of vehicles braking for lane change implies difficultness in obtaining the gap in the mainline traffic.

But also, during freeway merging maneuver, the on-ramp vehicles might decelerate and stop near or at the end of acceleration lane if there are no safe gaps for the merging vehicles to enter the mainline traffic. Brake ZX which is the braking for emergency stop occurs near or at the end of the acceleration lane.

Brake Cooperative

The performance of traffic operations on acceleration lane have impacts on the operations of mainline traffic. The vehicles in the mainline traffic need to create gaps to allow the vehicles from acceleration lane to merge. For good operations in merging area, the gaps should be created just before the merging influence area. Creation of gaps involve deceleration and acceleration whereby the deceleration of mainline traffic results to braking which is referred to as brake cooperative.

When several vehicles are associated with brake cooperative in merging area, it means the gaps that were present were not accepted by merging vehicles hence they do need to create gaps that will be accepted. But if the vehicles from ramp have been able to merge without the mainline traffic braking, it means that the present gaps are enough, although the gaps creation might as well be due to acceleration of leading vehicle while a lagging vehicle maintains a uniform speed.

CMAS is sought to reduce the number of brake cooperative in the merging area. When vehicles in the mainline approaches the merging area, they receive advisory messages on the decisions to take based on merging algorithm. The vehicle will either change lane, accelerate or decelerate to allow the best action to be taken in the merging area by the merging vehicles. This implies that, at the merging area the vehicles in the outer most lane will be travelling at an advisory speed and do not need to brake (brake cooperative) for the aging drivers to merge as the gaps will already be created prior to merging area.

Hard Braking

When a driver on-ramp is approaching the merging area with lower speed than the speed of freeway traffic, need to increase the speed of the vehicle so that it matches the speed of the mainline traffic to facilitate safe and efficient merging. Merging with low speed results to higher speed difference and can lead to shock waves upstream of the mainline traffic. Although, matching the speed of the mainline traffic still does not guarantee enough gap to merge into the freeway. Lack of acceptable gaps results to need of decelerating because there are some restrictions like other preceding vehicles still on the acceleration lane and the end of acceleration lane.

The deceleration rate will depend on the speed and presence of another vehicle ahead and the distance to the end of acceleration lane. The presence of other vehicles in the acceleration lane may result to rear end collision. Therefore, hard braking details obtained from deceleration rates were used to evaluate the potential benefits of the merging assistance system in creating enough gaps to avoid such type of breaking which is the likelihood of rear end collision occurrence. A deceleration rate of 14.8ft/s^2 was set as a threshold for hard braking in accordance with the Green Book (AASHTO, 2011).

Results and Discussions on Sensitivity Analysis

Results

The percentages of vehicles driven by aging drivers that applied brakes to wait for another gap to merge (brake LC) for the two site locations are shown in Figure 5.1, while Figure 5.2 shows the percentage of vehicles driven by aging drivers braking for an emergency stop during the freeway merging maneuver. Figure 5.3 provides the trend of cooperative braking for mainline traffic at different rates of CV penetration with varying aging driver compositions and varying traffic demand at both Corkscrew and Pine Ridge merging areas. Figure 5.4 shows older drivers decelerating faster than 14.80 ft/s^2 expressed as a percentage of all vehicles driven by older drivers for both the Corkscrew and Pine Ridge acceleration lanes.

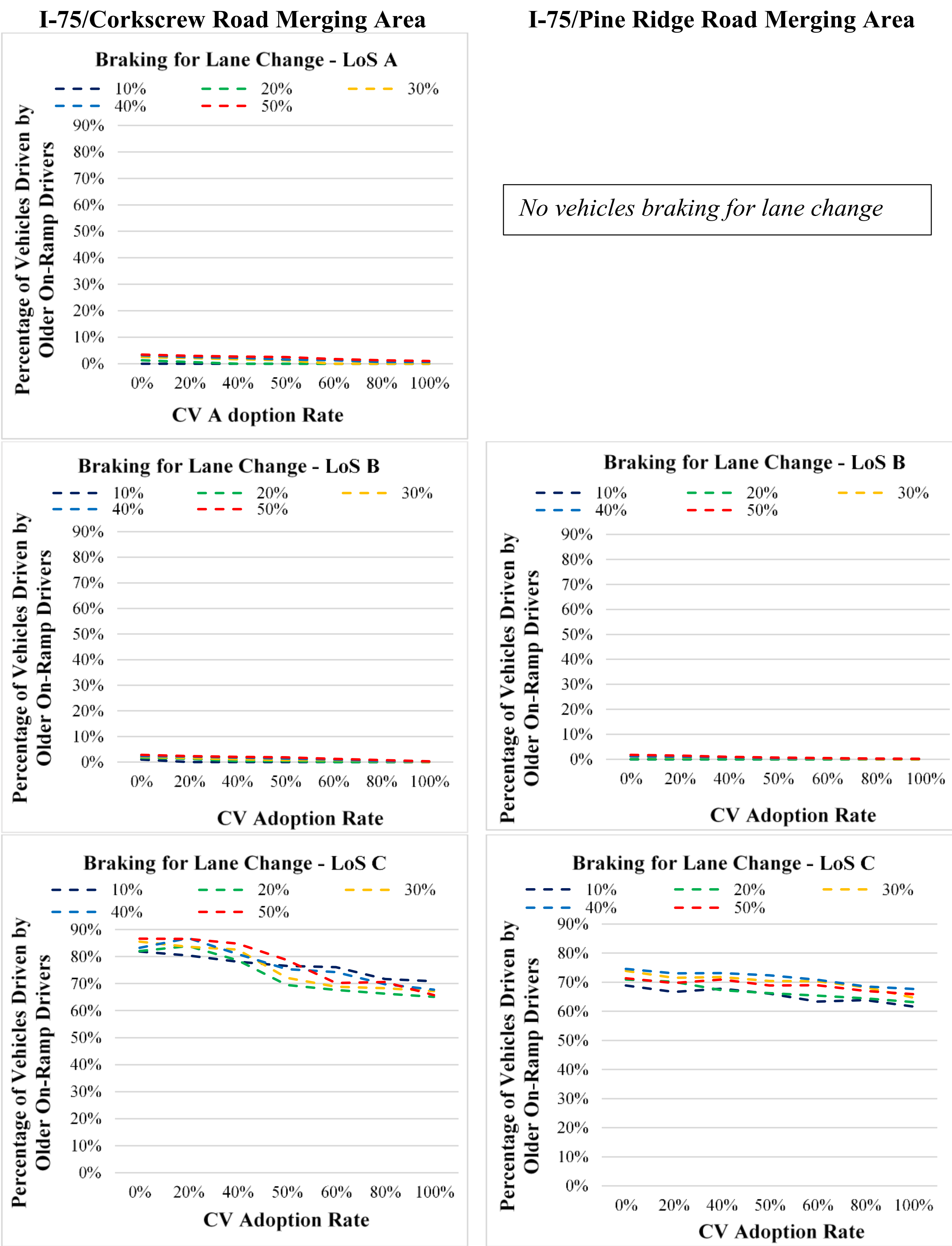


Figure 5.1: Braking for Lane Change by Vehicles Driven by Older On-Ramp Drivers

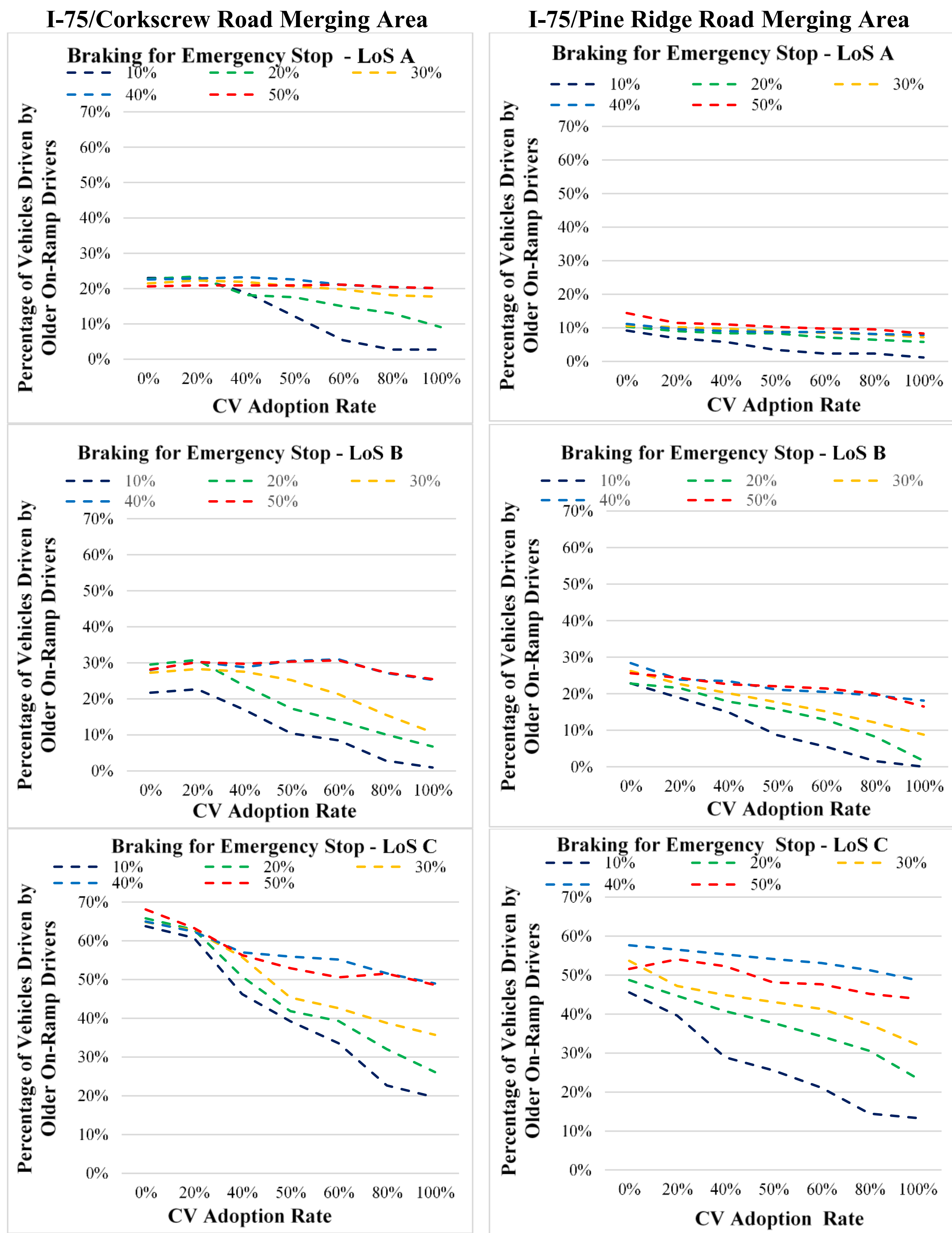


Figure 5.2: Braking for Emergency Stop by Vehicles Driven by Older On-Ramp Drivers

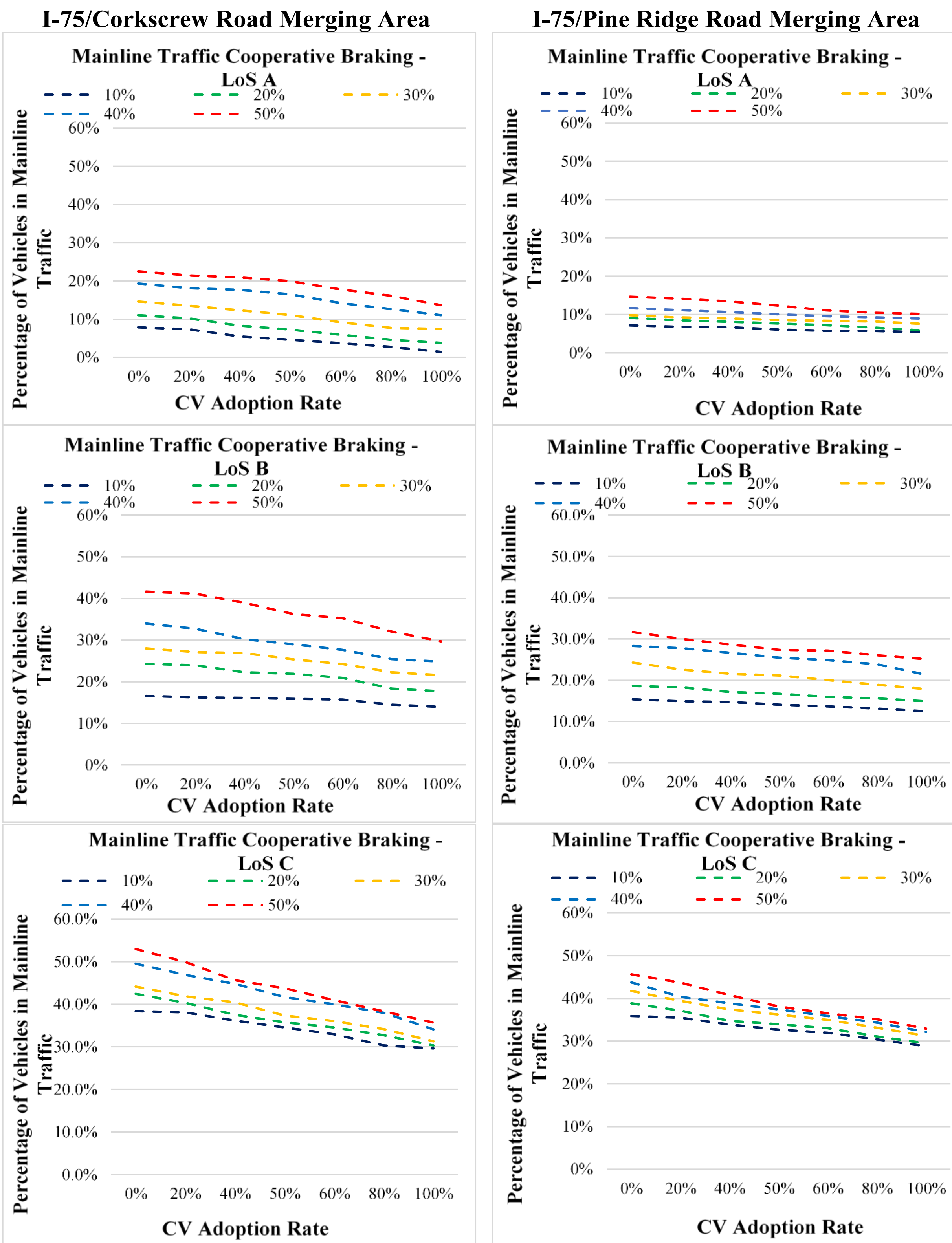


Figure 5.3: Brake Cooperative by Vehicles in Mainline Traffic in the Right Most Through Lane

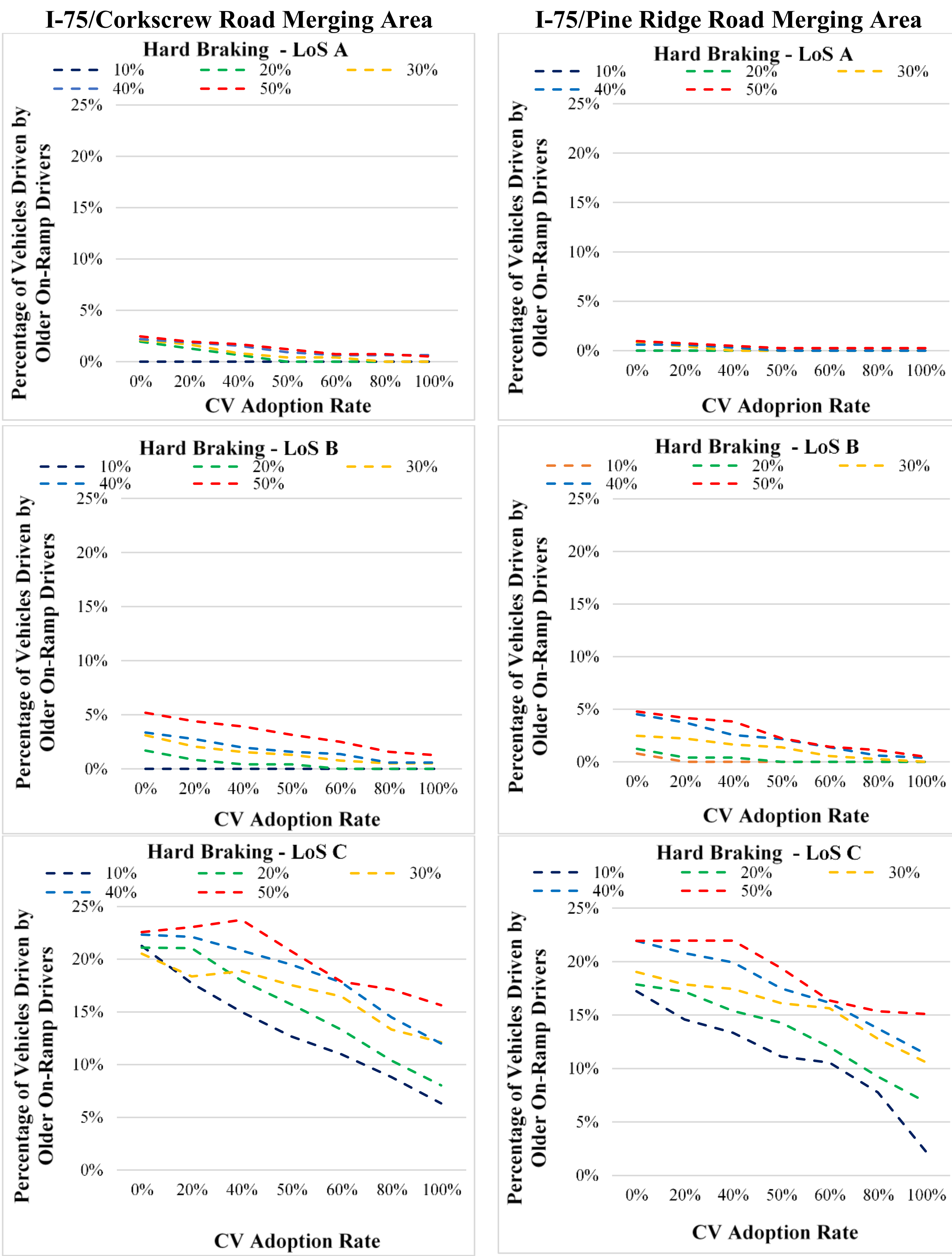


Figure 5.4: Hard Braking by Vehicles Driven by Older On-Ramp Drivers

Discussions

Vehicle interaction states and the rate of deceleration (hard braking) which are also the MOEs in this study showed a relationship to safety. On freeways, vehicles are not expected to stop, except for emergencies, and vehicles traveling along an on-ramp should match the mainline traffic speed to avoid disruptions and shockwaves in the mainline traffic flow. If vehicles are braking for a lane change or an emergency stop on the acceleration lane, it indicates that they have failed to merge. Braking for lane change may lead to rear-end crashes, depending on the speed of the vehicle(s) following in the acceleration lane. Braking for an emergency stop indicates that the vehicle failed to merge within the limits of the acceleration lane and stopped at the end of acceleration. This scenario implies an increased difficulty in entering the freeway due to higher vehicle speeds on the mainline. Joining mainline traffic from a stopped position may lead to rear-end crashes or side swipe crashes. If many vehicles in the mainline traffic (especially the right outermost lane) are braking (cooperative braking) to allow vehicles from the on-ramp to merge, safety will be compromised as other vehicles will be decelerating at a higher rate and some will change lanes. These scenarios may lead to rear-end and side swipe crashes. If the rate of deceleration of these types of braking (lane change, emergency stop, or cooperative) exceeds the threshold (14.8ft/s^2) (AASHTO, 2011), a rear-end crash could occur**.**

Braking for Lane Change and Emergency Stop

At any LOS, the introduction of connected vehicles reduced the percentage of vehicles braking for lane change. The percentage of vehicles braking for lane change was smaller than the percentage for vehicles braking for emergency stop at LOSs A and B. The pattern changed when traffic demand increased to LOS C. With low traffic demand, vehicles had room to accelerate with intention of catching the speed of mainline traffic but eventually they needed to apply brakes once they were near or at the end of acceleration lane with no gap to merge into mainline traffic. With higher traffic demand, the room for accelerating was restricted by the number of vehicles on the acceleration lane, hence vehicles applied brakes for lane change from the beginning of the acceleration lane. Having difficulties in moving forward, vehicles intended more on merging and fewer vehicles reached the end of the acceleration lane then applied brakes for emergency stop.

For the longer acceleration lane and fewer aging on-ramp drivers, the percentage of older drivers braking for lane change was lower and decreased significantly when CMAS was employed. With the shorter acceleration lane (Corkscrew entrance), braking for lane change for a low composition of aging drivers depended on traffic demand. At low traffic demand (LOS A), there were no aging drivers (0%) braking for lane change at longer acceleration lane (Pine Ridge Entrance). However, braking for lane change increased with the increase in traffic demand.

When CMAS was employed, the rate of change in braking for an emergency stop was higher at the site with a longer acceleration lane (Pine Ridge entrance) than at the site with a shorter acceleration lane (Corkscrew entrance). At any LOS, the percentage of older drivers braking for an emergency stop decreased as the CV adoption rate increased, except for some intermediate CV adoption rates (20% to 60%) at the Corkscrew entrance. This increase in number of vehicles braking for emergency stop can be explained as a scenario whereby either a leading vehicle or lagging vehicle is not a connected vehicle hence there is no enough cooperation in creating the gaps though the connected vehicles in most outer lane will try creating gaps, but the conventional vehicles won't cooperate leading to increase in conflicts and fail to provide enough gap for merging vehicles.

Table 5.1 provides the percentage reduction of brake ZX and brake LC between 0% of connected vehicles in the mainline traffic and when the CV adoption rate is at 100%.

Table 5.1: Percentage Reduction of Brake ZX and Brake LC

LoS	Composition of aging drivers	Brake ZX (emergency stop)		Brake LC (lane change)	
		Longer Acceleration lane	Shorter Acceleration Lane	Longer Acceleration lane	Shorter Acceleration Lane
A	10%	87.5%	88.2%	N/A	N/A
	20%	43.8%	60.0%	N/A	100%
	30%	32.0%	17.7%	N/A	100%
	40%	29.7%	11.1%	N/A	80.0%
	50%	42.4%	2.4%	N/A	71.4%
B	10%	100%	95.7%	N/A	100%
	20%	92.7%	77.1%	N/A	100%
	30%	66.3%	61.0%	100%	100%
	40%	36.1%	9.9%	83.3%	91.7%
	50%	35.6%	9.5%	90.9%	88.9%
C	10%	70.7%	69.2%	10.5%	13.4%
	20%	51.9%	60.4%	10.9%	20.7%
	30%	40.1%	44.9%	12.4%	21.4%
	40%	15.7%	24.6%	9.3%	18.6%
	50%	14.8%	28.6%	7.7%	24.2%

The percentage reduction in the two types of braking depended on traffic conditions, length of acceleration lane, and composition of aging on-ramp drivers. When CMAS was employed, a greater reduction in both types of braking was observed on the longer acceleration lane (at least 1500 ft) when the traffic demand was low with fewer aging on-ramp drivers.

Brake Cooperative

CMAS reduced the number of brake cooperatives in the merging area. When vehicles in the mainline approach the merging area, they receive advisory messages on the decisions to take. The mainline vehicle can either change lanes, accelerate, or decelerate to allow for the best action to be taken in the merging area by the merging vehicles. This allows a mainline vehicle in the outermost lane to travel at an advisory speed, with no need to brake (brake cooperative) for the aging drivers to merge, as the gaps will already be created prior to the merging area. Table 5.2 provides the percentage reduction of brake cooperative between 0% of connected vehicles in the mainline traffic and when the CV adoption rate is at 100%.

Table 5.2: Percentage Reduction in Brake Cooperative

LoS	Composition of aging drivers	Brake Cooperative	
		Longer acceleration lane	Shorter acceleration lane
A	10%	25.1%	82.2%
	20%	36.6%	65.5%
	30%	23.3%	49.4%
	40%	23.2%	42.8%
	50%	31.0%	39.4%
B	10%	18.9%	16.0%
	20%	20.1%	27.0%
	30%	26.3%	23.0%
	40%	24.8%	26.8%
	50%	20.7%	28.6%
C	10%	19.8%	22.7%
	20%	24.0%	28.6%
	30%	25.2%	29.2%
	40%	26.6%	31.2%
	50%	27.8%	32.6%

The percentage of vehicles braking to allow vehicles to merge (brake cooperative) decreased with an increase in CV adoption rate. The reduction margin was nearly the same (standard deviation of 4.61%) for the longer acceleration lane, while the standard deviation of percentage reduction for the shorter acceleration lane was 17.6%. Keeping other factors constant, the longer acceleration lane performed better than the shorter acceleration lane, as the percentages of brake cooperative were low, and thus, the margins of reductions in cooperative braking when CMAS was employed were also low with the longer acceleration lane location.

Hard Braking

CMAS reduced the percentage of vehicles that decelerated at a rate greater than 14.80 ft/s^2. With low traffic demand, the reduction was up to 100%. The percentage reduction of hard braking was similar for both acceleration lane lengths studied. This finding is the result of basic safety messages which advise drivers on the speed and actions to pursue. Regardless of the length of acceleration lane, the CMAS demands similar operations, and by doing so, hard braking remains a variable that mainly depends on traffic demands and composition of aging on-ramp drivers. Table 5.3 provides the percentage reduction of hard braking between 0% of connected vehicles in the mainline traffic and when the CV adoption rate is at 100%.

Table 5.3: Percentage Reduction in Hard Braking

LoS	**Composition of older drivers**	**Hard braking**	
		Longer acceleration lane	**Shorter acceleration lane**
A	10%	N/A	N/A
	20%	N/A	100%
	30%	100%	100%
	40%	100%	71.4%
	50%	75.0%	80.0%
B	10%	100%	N/A
	20%	100%	100%
	30%	100%	83.3%
	40%	91.3%	82.4%
	50%	90.0%	75.8%
C	10%	87.1%	70.2%
	20%	61.6%	62.0%
	30%	44.4%	41.0%
	40%	48.2%	46.2%
	50%	31.2%	30.8%

Results and Discussions on Statistical Analysis

Braking for lane change, braking for emergency stop, cooperative braking, and hard braking were the VISs Measure of Effectiveness that were statistically analyzed in this study. The Mann-Kendall statistical test was then used to determine whether a significant trend existed, and whether the trend was positive or negative for the variable of interest over time. The Mann-Kendall statistical test is a widely used non-parametric test that is used for determining trends in a time series (Hamed & Rao, 1998). Since the rate of CV penetration increases over time, CV penetration rate was then considered as a time series variable. XLSTAT add-in was used in Excel at a 95% confidence level with the null hypothesis (H_o) stating that there was no trend in the series, tested against the alternative hypothesis (H_a) stating that a trend was present in the series. Table 5.4 provides the results obtained from the Mann-Kendall test statistic for the VISs at different aging driver compositions.

About 120 trend tests were supposed to be conducted; however, 12 tests were not possible to conduct as the sequences were constant (0.0%). For the 108 Mann-Kendall trend tests performed, there was not enough evidence to reject the null hypothesis for 7 of tests. For the remaining 101 tests, the null hypothesis was rejected at a 95% confidence level since the computed *p*-value was lower than the significance level alpha (0.05), and the alternative hypothesis which stated that "there is a trend in the series" was accepted. With the Kendall's τ values ranging from -1 to less than 0 ($-1 \leq$ Kendall's $\tau < 0$), results show a decreasing trend. The negative correlation signifies that an increase in connected vehicle penetration in the network reduces the number of interaction states.

Table 5.4: Results of Mann-Kendall Trend Test for Aging Drivers Interaction States

LOS	Location	VIS	Kendall's tau					p-value				
			Composition of older drivers on-ramp					Composition of older drivers on-ramp				
			10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
A	I-75 at Pine Ridge road	B-Cop	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		B-LC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		B-ES	-0.976	-0.976	-1	-0.976	-1	0.004	0.004	0.003	0.004	0.003
		HB	n/a	n/a	-0.724	-0.816	-0.825	n/a	n/a	0.057	0.027	0.019
	I-75 at Corkscrew road	B-Cop	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		B-LC	n/a	-0.724	-0.926	-0.976	-1	n/a	0.057	0.008	0.004	0.003
		B-ES	-0.951	-0.905	-0.810	-0.683	-0.206	0.006	0.007	0.016	0.048	0.638
		HB	n/a	-0.845	0.951	-0.926	-0.976	n/a	0.019	0.006	0.008	0.004
B	I-75 at Pine Ridge road	B-Cop	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		B-LC	n/a	n/a	-0.926	-0.951	-1	n//a	n/a	0.008	0.006	0.003
		B-ES	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		HB	-0.535	-0.816	-1	-1	-1	0.211	0.027	0.003	0.003	0.003
	I-75 at Corkscrew road	B-Cop	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		B-LC	-0.535	-0.900	-0.976	-1	-1	0.211	0.011	0.004	0.003	0.003
		B-ES	-0.905	-0.905	-0.810	-0.143	-0.143	0.007	0.007	0.016	0.764	0.764
		HB	n/a	-0.900	-0.976	-0.976	-1	n/a	0.011	0.004	0.004	0.003
C	I-75 at Pine Ridge road	B-Cop	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		B-LC	-0.810	-1	-0.905	-0.905	-0.810	0.016	0.003	0.007	0.007	0.016
		B-ES	-1	-1	-1	-1	-0.810	0.003	0.003	0.003	0.003	0.016
		HB	-1	-1	-1	-1	-0.810	0.003	0.003	0.003	0.003	0.016
	I-75 at Corkscrew road	B-Cop	-1	-1	-1	-1	-1	0.003	0.003	0.003	0.003	0.003
		B-LC	-1	-0.905	-1	-0.905	-0.905	0.003	0.007	0.003	0.007	0.007
		B-ES	-1	-1	-1	-1	-0.905	0.003	0.003	0.003	0.003	0.007
		HB	-1	-1	-0.905	-1	-0.714	0.003	0.003	0.007	0.003	0.035

Note: B-Cop = Brake Cooperative, B-LC = Braking for lane change, B-ES = Braking for emergency stop, HB = Hard braking, n/a = Mann-Kendall trend test not applicable

A total of 101 (93.5%) out of 108 tests performed showed significance decrease at 95% confidence level. The graphs for interaction states from Vissim simulations generally indicated a decrease in interaction states when CMAS was employed despite some abnormal variations in some of the CV adoption rates due to a mixture of connected and traditional vehicles operations. Thus, it was agreed that there was a decreasing trend (as also suggested by Kendall's tau) which showed employment of CMAS reduced the interaction states being analyzed.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Driving tasks are more challenging for aging drivers that may experience declining capabilities related to age. Moreover, merging onto a freeway presents added difficulty for older drivers to perform simultaneous actions in quick succession. Emerging technologies, such as connected vehicle (CV) can assist aging drivers with freeway merging maneuvers.

This study utilized the Vissim models created by a previous study (Lwambagaza, 2016) and the developed algorithm for Cooperative Merging Assistance System (CMAS) which utilizes CV technology. The developed CMAS utilized connected vehicle technology to enhance freeway merging maneuvers, using a connected vehicle environment created in Vissim through Component Object Model (COM) interface. Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V) wireless communication between connected vehicles were modeled using the Car2x (Car to everything) Application Programming Interface (API).

To evaluate the performance of CMAS, a sensitivity analysis was conducted for varying CV penetration rates, composition of aging on-ramp drivers, and mainline and on-ramp traffic flows under different levels of service. Merging location, merging speed and vehicle interaction states were used as measures of effectiveness.

Results indicate that CMAS helps elderly drivers merge earlier into mainline traffic before reaching the end of acceleration lane. For the same conditions of traffic demand and composition of older drivers, there was a greater reduction in late merges on the longer acceleration lane when CMAS was employed, compared to the shorter acceleration lane. Although findings reveal that reduction in late merges by aging drivers was a function of acceleration lane length, level of service, and CV penetration rate, CMAS reduced the percentage of late merges. Statistical analysis showed that the reduction in late merges is significant in all conditions with higher traffic demand.

When traffic demand is low, at 95% confidence level the reduction in late merges can either be significant or insignificant.

CMAS, which utilizes CV technology, did not significantly affect the merging speed of aging drivers. A vehicle merging early from the acceleration lane may have the same speed as a vehicle merging at the center or end of the acceleration lane for similar traffic conditions. This finding is consistent with a previous study (Lwambagaza, 2016). Although the longer acceleration lane provides more distance to accelerate prior to merging, average merging speeds of aging drivers were nearly the same as speeds observed on the shorter acceleration lane. At 95% confidence level, a z-test for the mean speeds showed that there is not difference in speed when CMAS is employed and when CMAS is not employed.

The vehicle interaction states used in the analysis included braking for lane change, braking for emergency stop, and brake cooperative (for mainline traffic). Since these interaction states are all associated with a braking action, the deceleration rate (hard braking) was also incorporated into the analysis. A statistical analysis was conducted using the Mann-Kendall trend test to determine the significance of the trends at a 95% confidence level.

The effect of traffic demand, composition of aging drivers, and length of acceleration lane on the percentage of vehicles braking for lane change showed a reduction with a CMAS. For the on-ramp with a longer acceleration lane (approximately 1500 ft), there were no aging drivers braking for lane change with low mainline traffic demand. Similar results were observed for the on-ramp with a shorter acceleration lane (approximately 1000 ft) when the ramp composition of aging drivers was lower than 20%. At both study sites, with an increase in mainline traffic demand, the percentage of aging drivers braking for lane change increased with an increase in the ramp composition of aging drivers. However, the percentage of aging drivers braking for lane change decreased with an increase in CV penetration rate.

An increase in CV penetration rate reduced the percentage of aging on-ramp drivers braking for emergency stops. With low mainline and on-ramp traffic demand (LOS A), the average reduction rate was 47.1% at the longer acceleration lane location compared to 35.9% at the shorter acceleration lane location. At LOS B, the average reduction rate in the percentage of aging on-ramp drivers braking for emergency stops was 66.1% to 50.6%, while the pattern changed with higher traffic demand (LOS C), where the reduction rate was 38.6 % for the longer acceleration lane compared to 45.6% for the shorter acceleration lane.

CMAS reduced the percentage of mainline traffic vehicles having to brake to allow merging vehicles to enter the freeway by enabling vehicles to communicate with each other. This allowed gaps to be created for on-ramp vehicles by either accelerating, decelerating, changing lanes, or doing nothing, depending on prevailing traffic conditions. The reduction margin was nearly the same (standard deviation of 4.61%) for the longer acceleration lane, while the standard deviation of percentage reduction for the shorter acceleration lane was 17.6%.

The percentage of aging drivers braking hard in the acceleration lane can be minimized when utilizing connected vehicle technology. CMAS helped aging on-ramp drivers to merge early onto the freeway by creating gaps in mainline traffic, thus reducing the number of vehicles in acceleration lane and decreasing the likelihood of hard braking. The sensitivity analysis showed that CMAS reduces the percentage of interaction states regardless of the composition of aging on-ramp drivers or traffic demand and length of acceleration lane. The statistical analysis revealed a trend in reduction of the percentages of interaction states. These reductions indicate that CMAS enhances the safety of aging drivers in freeway merging areas.

Implementation of the Proposed Algorithm

The proposed algorithm is designed to be implemented in vehicles with conditional automation. Table 6.1 provides description on the levels of automation as defined by the Society of Automotive Engineers (SAE). In the conditional automation (automation level 3), the environment is monitored by the system and also the control of actuators is done by the system. The proposed algorithm enables the communication between vehicles whereby each vehicle with the connected capabilities can communicate and assist the driver based on the conditions of the environment. The assistance to the on-ramp driver can be given by a means of either visual and/or auditory. The algorithm can be installed in the onboard unit and the information on the advised action can then be displayed on the dashboard screen. Figure 6.1 provides an ideal display on the dashboard screen when the on-ramp driver is advised to proceed with the merging maneuver.

Table 6.1: Levels of Automated Driving for Road Vehicles Defined by the Society of Automotive Engineers (SAE) (Source: Martínez & Jiménez, 2019)

SAE Level	Name	Control of Actuators	Monitoring of Environment	System Capability
0	No automation	Human driver	Human driver	n/a
1	Driver Assistance	Both	Human driver	Some DM [1]
2	Partial Automation	System	Human driver	Some DM [1]
3	Conditional Automation	System	System	Some DM [1]
4	High Automation	System	System	Some DM [1]
5	Full Automation	System	System	All DM [1]

[1] DM: Driving Modes.

Figure 6.1: Display on the Dashboard (for On-Ramp Vehicle) During Freeway Merging

Comparison with Concurrent Study

A study with similar theme as this study was conducted using a driving simulator. The study investigated the time it took older drivers in comparison with other younger drivers to complete merging maneuvers on freeways under different driving, traffic and geometric conditions in a driving simulator. The study found out that older drivers took longer time to complete merging maneuver on freeways compared to young drivers. The geometry of the merging area was also observed to have impact on merging maneuver. This finding is similar to what was found in this study although in this study the only geometric difference was the length of acceleration lane while the other similar study the geometric difference was the number of lanes (four and six lanes freeways).

Under different weather conditions, the study found that there is insignificant difference in time taken during merging in foggy weather compared to merging in clear weather. The tandem study also found that, with LOS A and B, there is insignificance difference in time taken to complete merging maneuver with the reason stated as a slight or, perhaps, inconsequential difference between the densities of the two levels. This finding is similar to this study as LOS A and B are observed to have almost similar impacts on traffic operations during merging maneuver.

Study Limitations

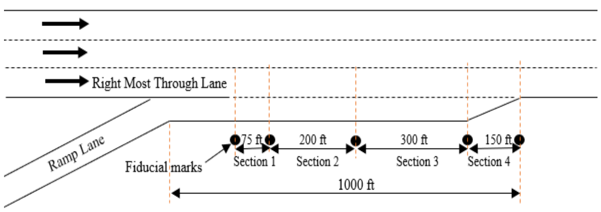
This study assumed that all connected vehicles obeyed the messages they received when in the merging area. Furthermore, the study assumed the effect of traffic operations on the mainline traffic in the merging area was limited to the merging vehicles, which is not always the case. Other limitations include the number of sites analyzed (only two) and the geometric characteristics of the two sites, i.e., 1000ft and 1500ft acceleration lengths. In addition, the effects of weather and vehicle types were not part of variables in evaluating the performance of CMAS.

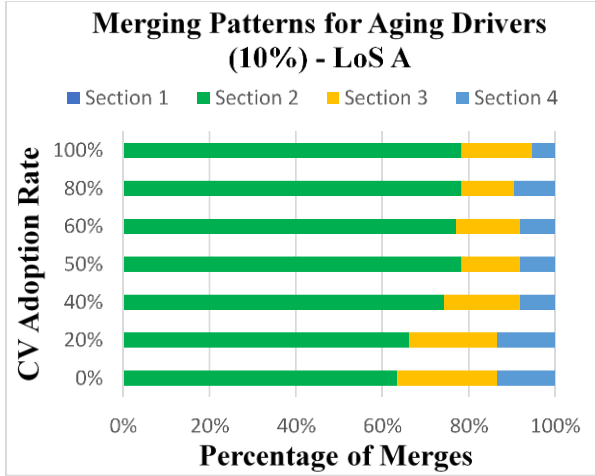
Recommendations for Future Work

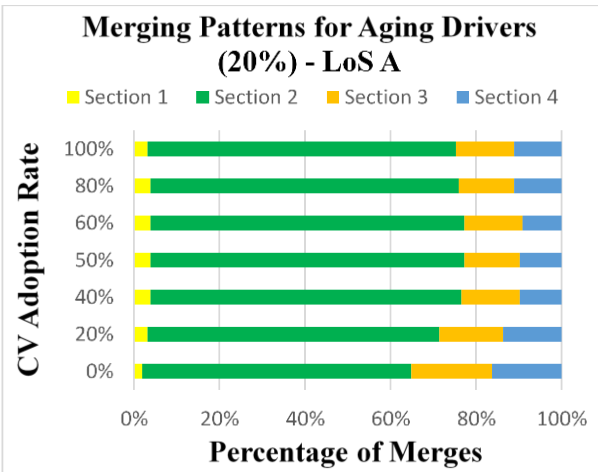
Further analysis is needed on the effects of traffic operations using other age groups of drivers to evaluate freeway merging maneuvers with and without CMAS. More interaction states can also be incorporated to expand the analysis to all driver age groups on acceleration lanes, as well as those in the mainline traffic. This knowledge can be beneficial in modifying the developed algorithm to enhance aging driver operations using connected vehicle technology. Also, a similar study using other methods, such as driving simulators and instrumented vehicles, to observe the effectiveness of the algorithm on enhancing aging driver freeway merging maneuvers could provide more realistic insights on what can be achieved by CV technology in a natural setting.

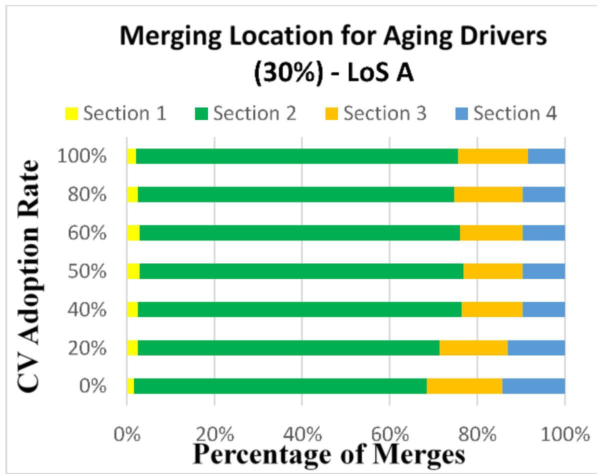
APPENDICES

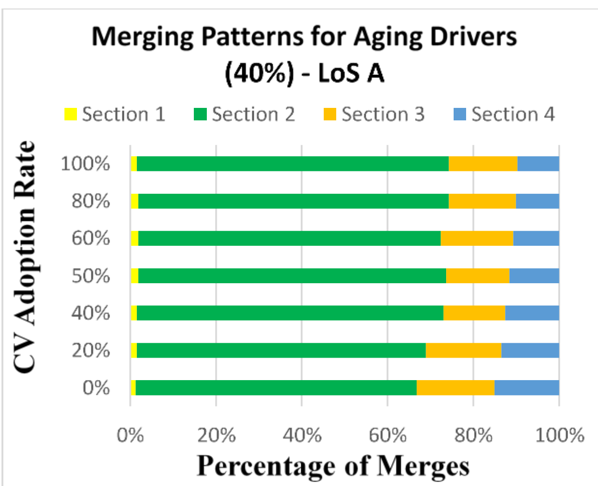
Appendix 1 – Merging patterns at Corkscrew entrance for various aging drivers' composition on-ramp for **LoS A**

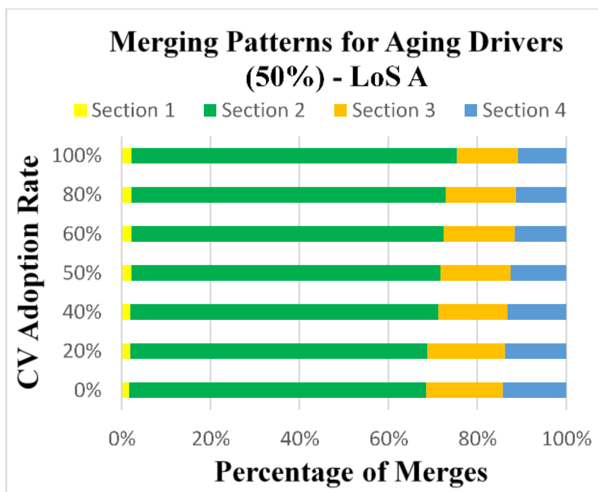




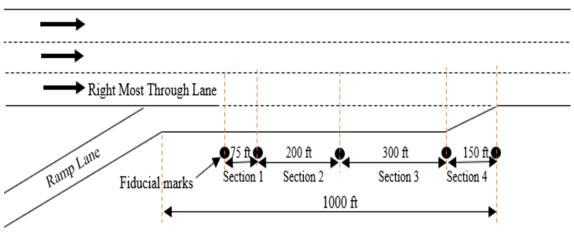


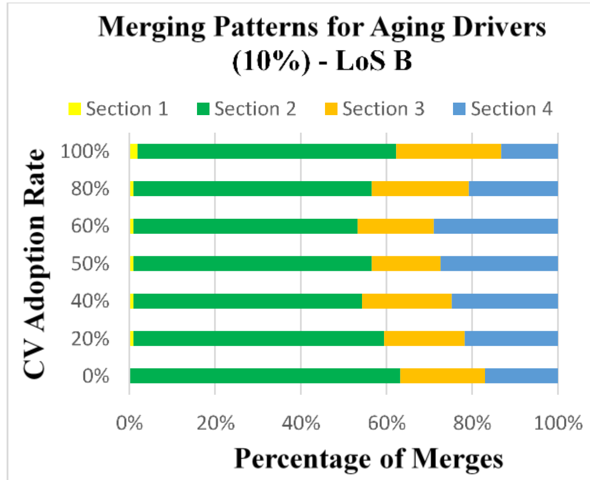


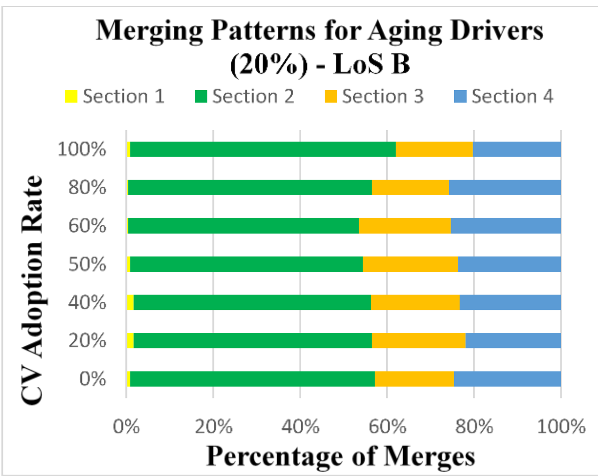


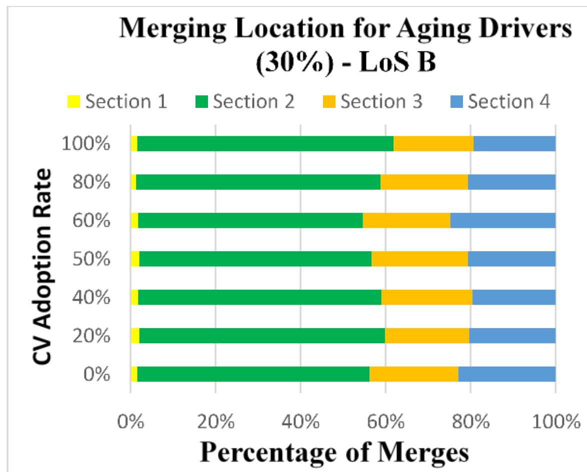


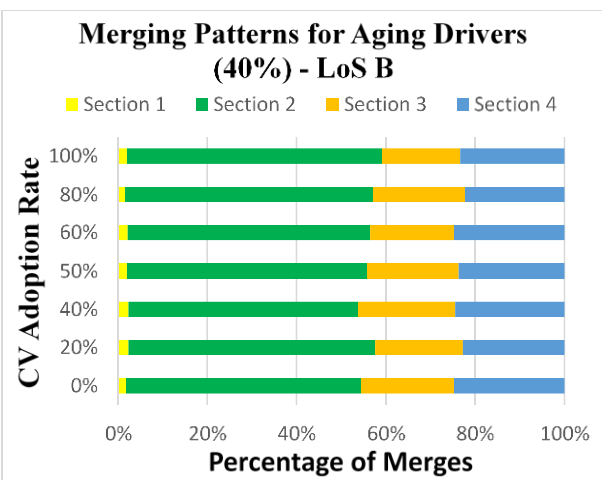
Appendix 2 – Merging patterns at Corkscrew entrance for various aging drivers' composition on-ramp for **LoS B**

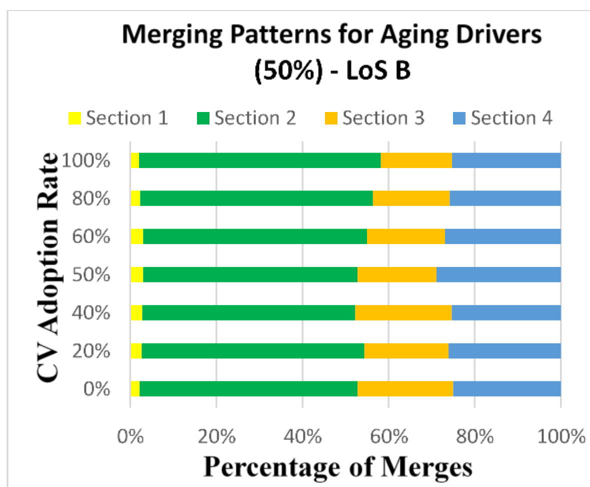




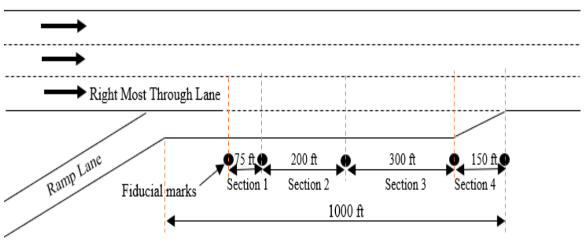


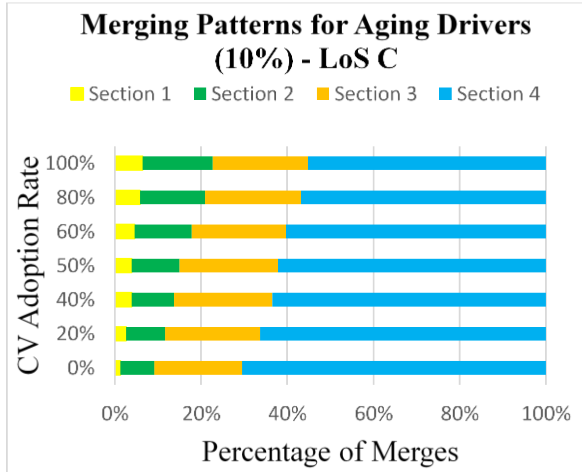


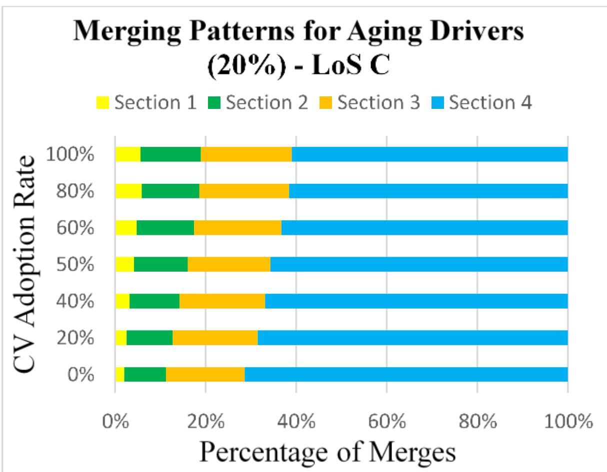


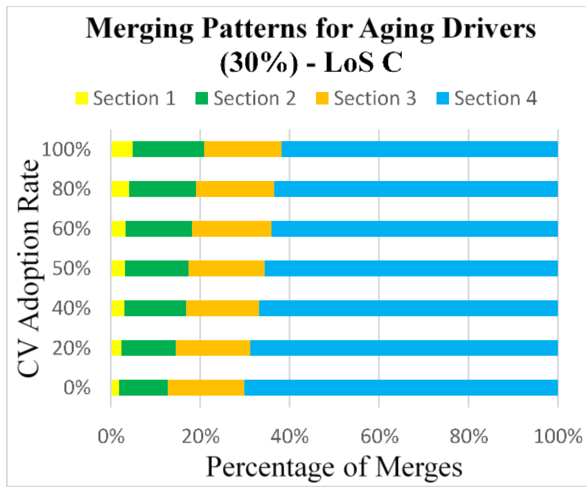


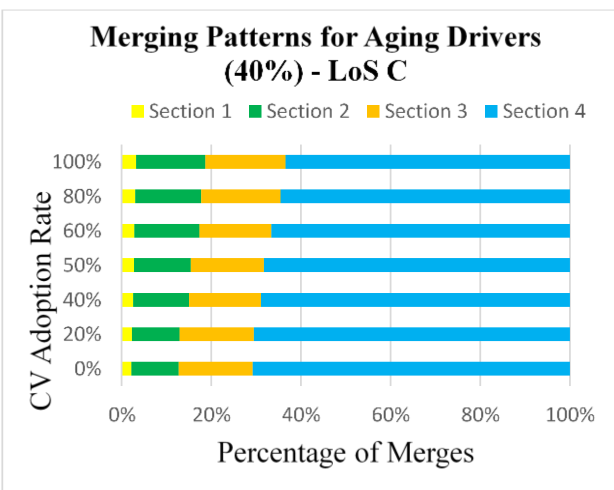
Appendix 3 – Merging patterns at Corkscrew entrance for various aging drivers' composition on-ramp for **LoS C**

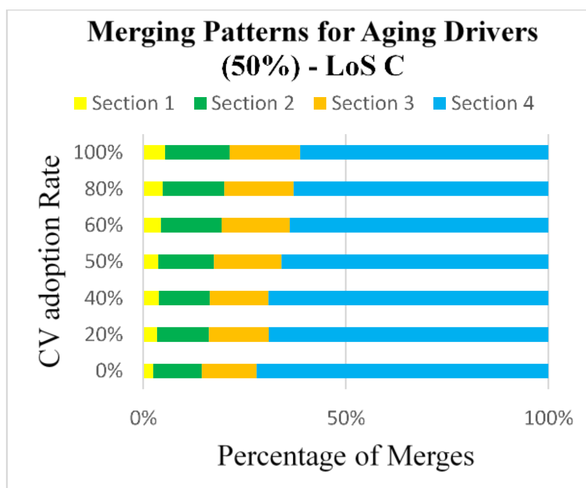




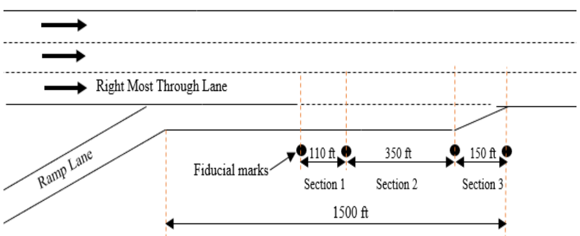


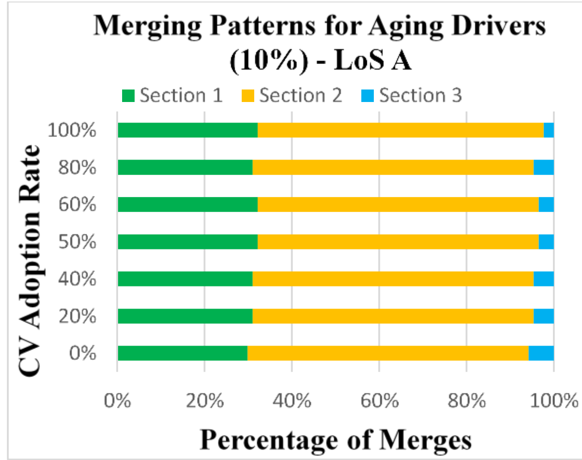


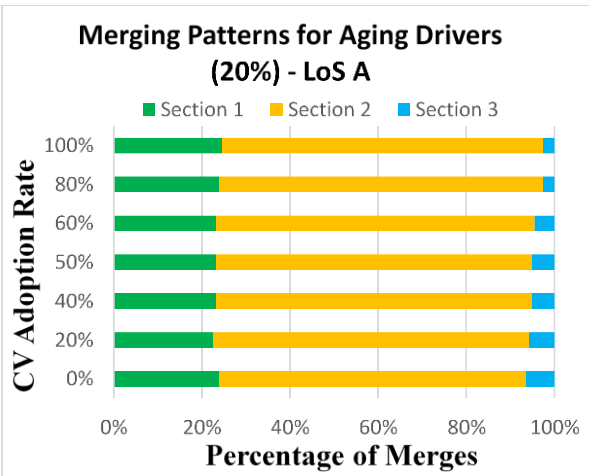


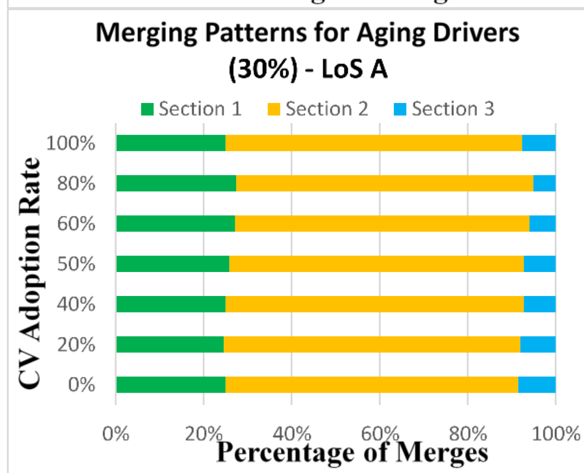


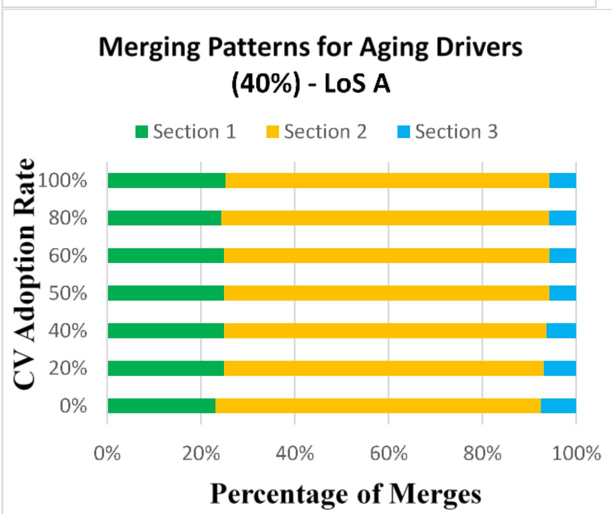
Appendix 4 – Merging patterns at Pine Ridge entrance for various aging drivers' composition on-ramp for **LoS A**

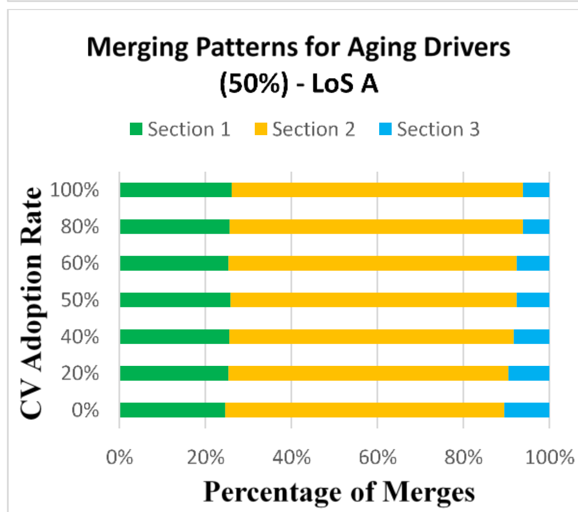




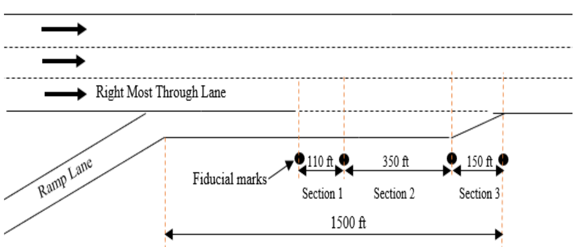


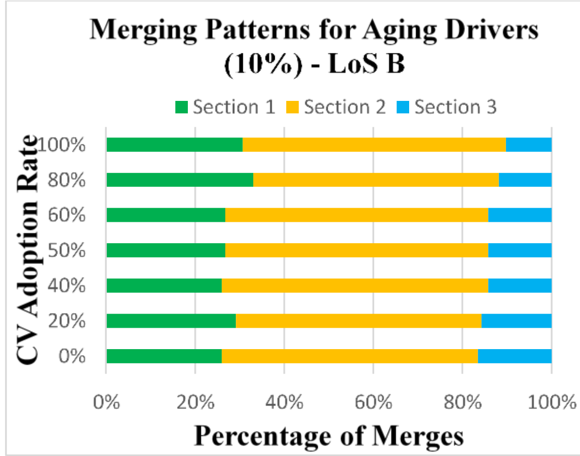


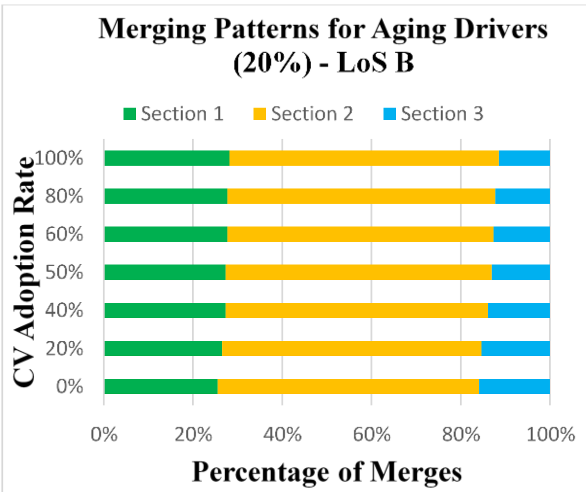


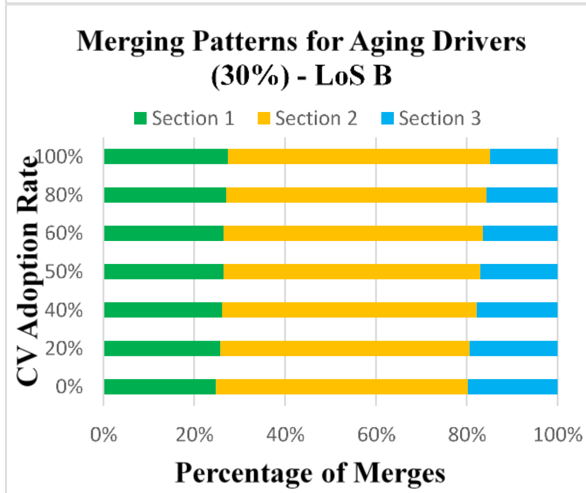


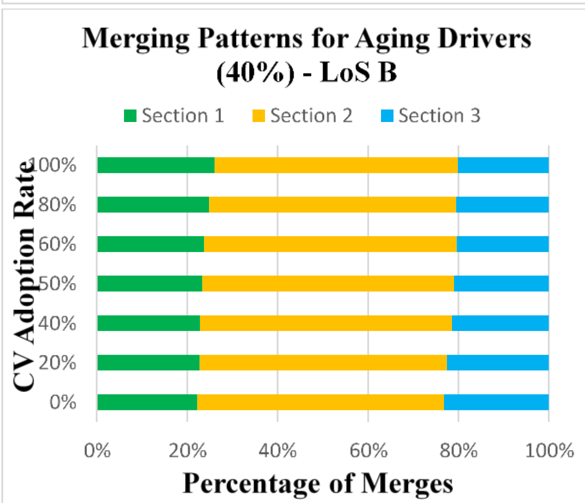
Appendix 5 – Merging patterns at Pine Ridge entrance for various aging drivers' composition on-ramp for **LoS B**

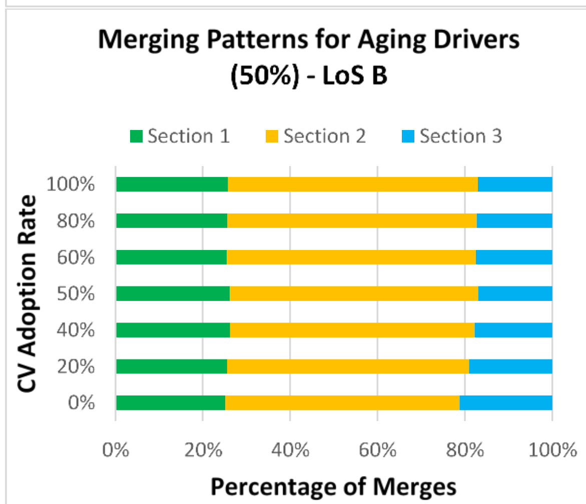




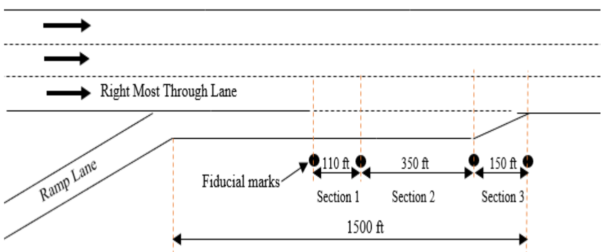


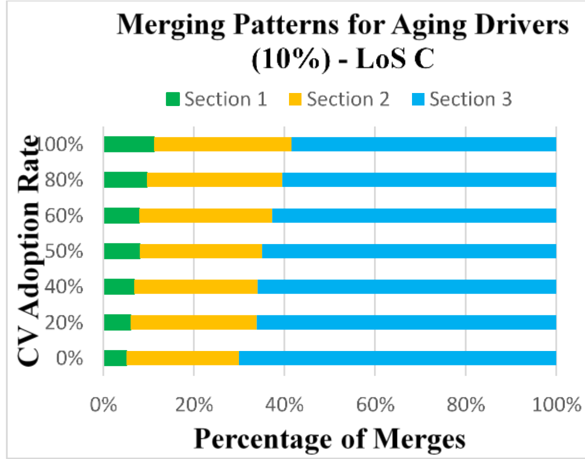


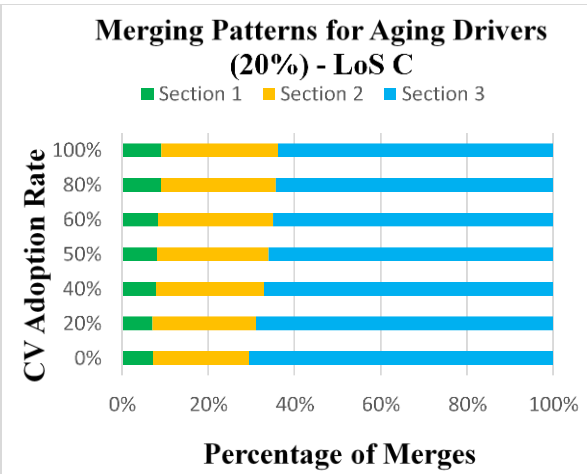


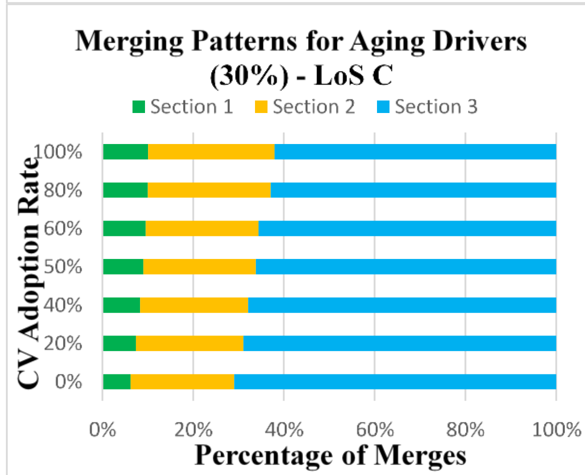


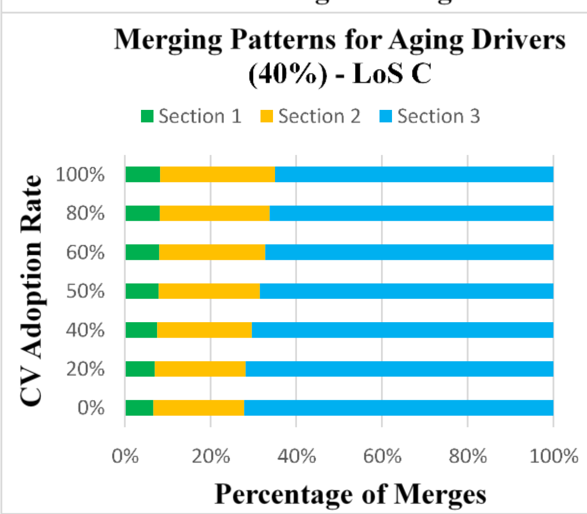
Appendix 6 – Merging patterns at Pine Ridge entrance for various aging drivers' composition on-ramp for **LoS C**

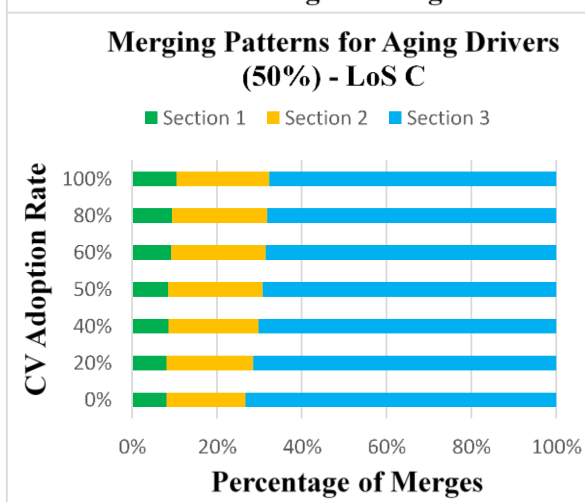




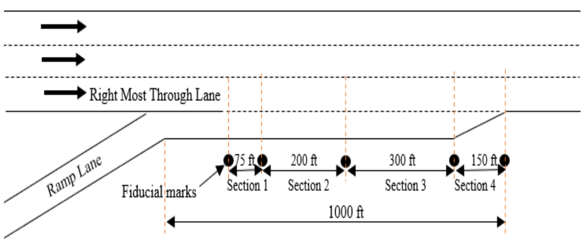


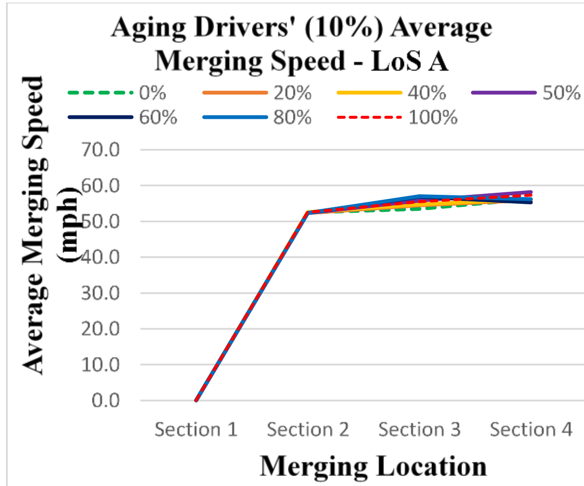


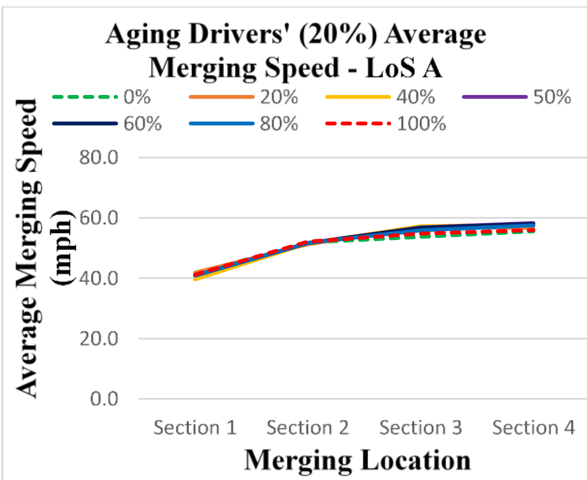


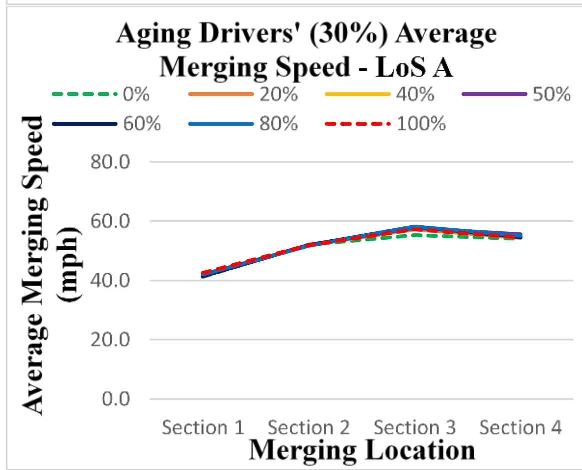


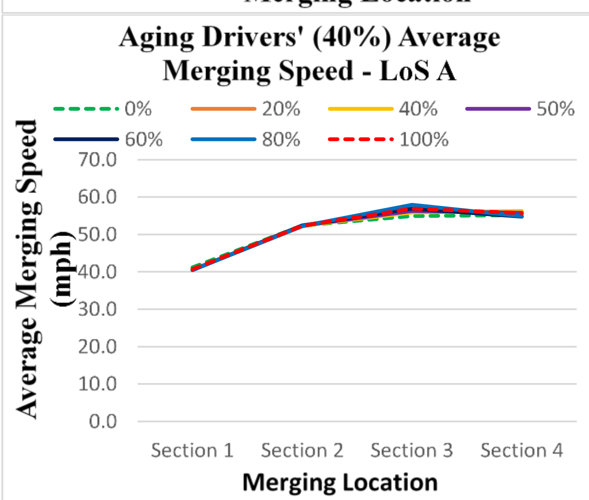
Appendix 7 - Average speed of older drivers during merging at Corkscrew entrance for various composition of aging drivers on-ramp for **LoS A**

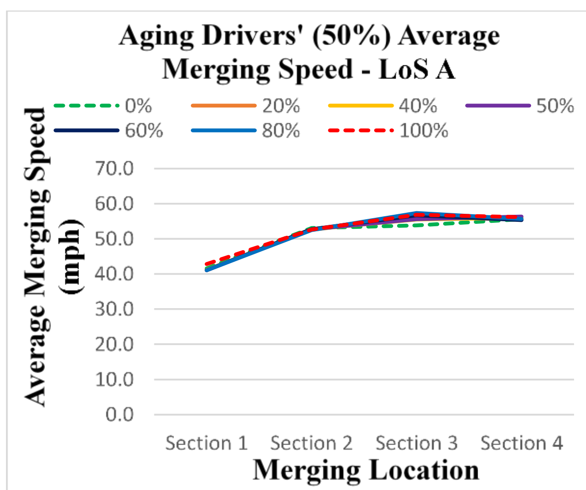




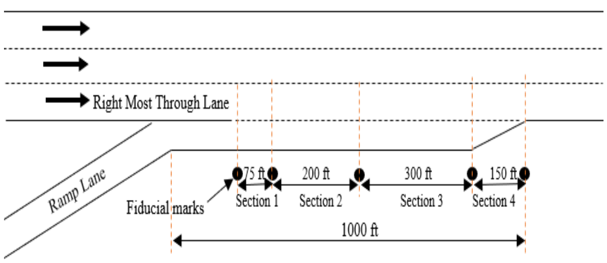


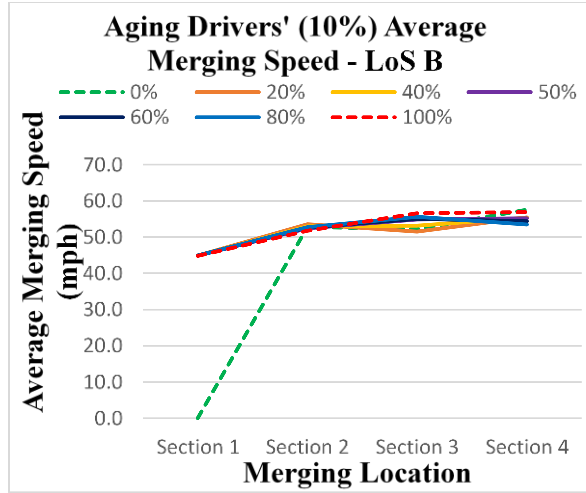


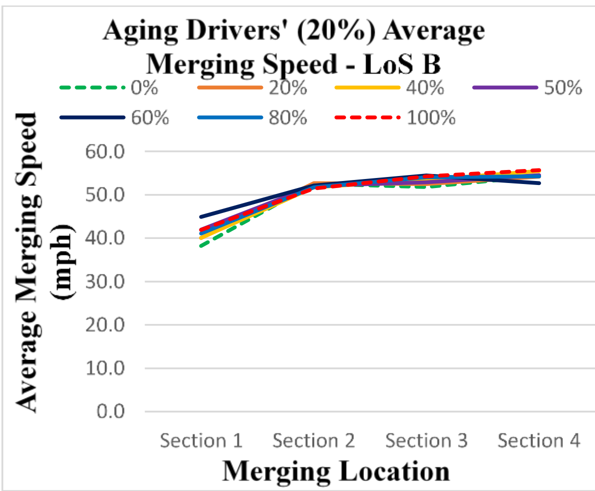


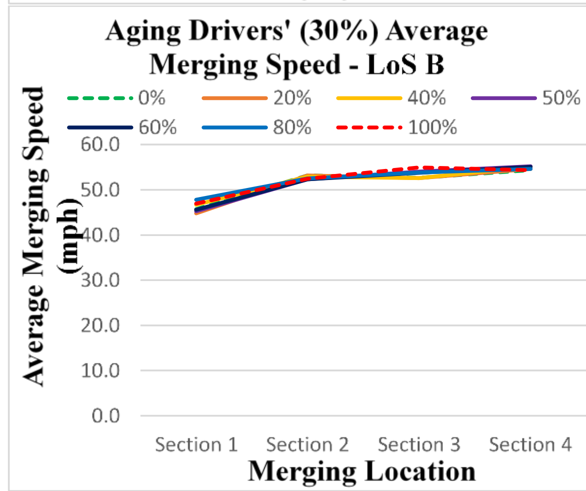


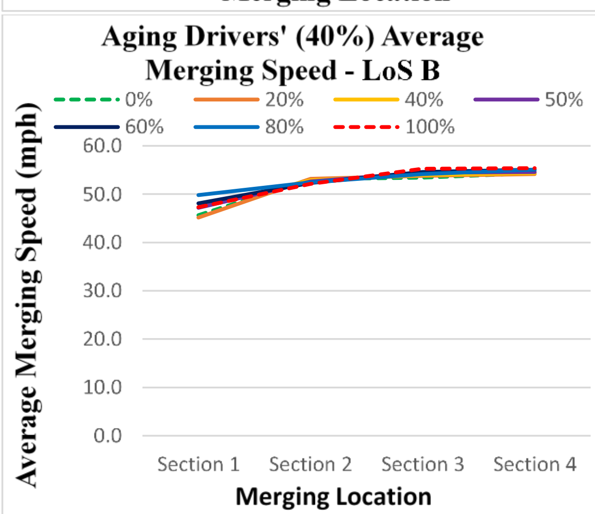
Appendix 8 - Average speed of older drivers during merging at Corkscrew entrance for various composition of aging drivers on-ramp for **LoS B**

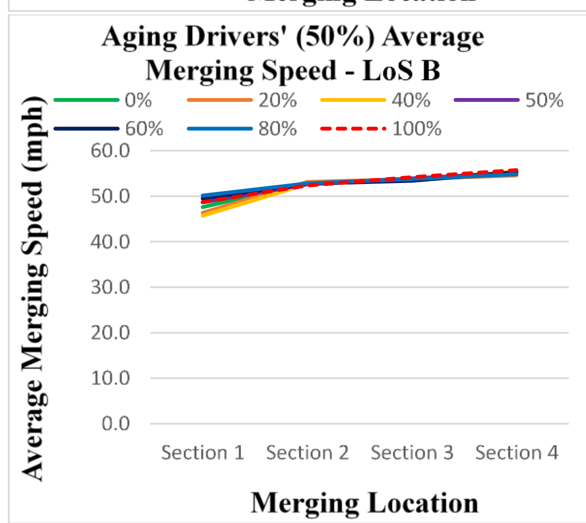




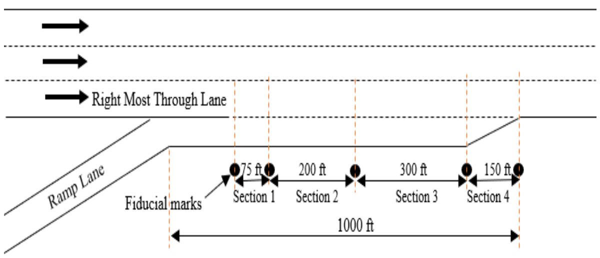


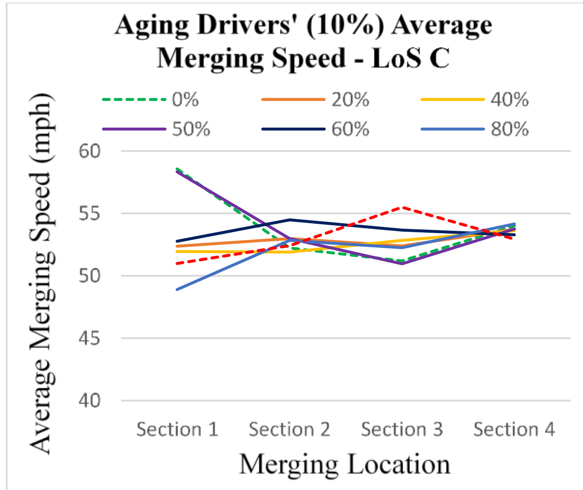


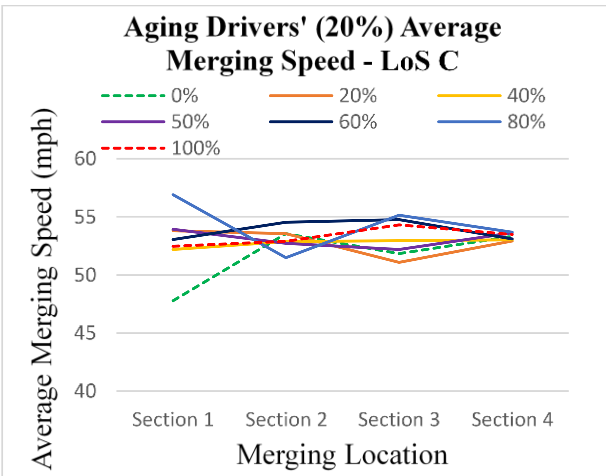


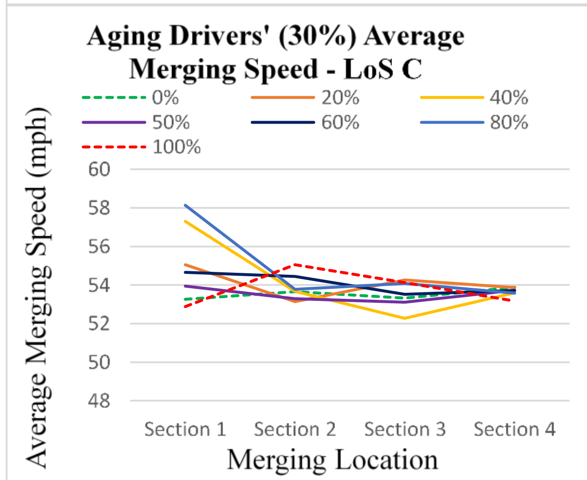


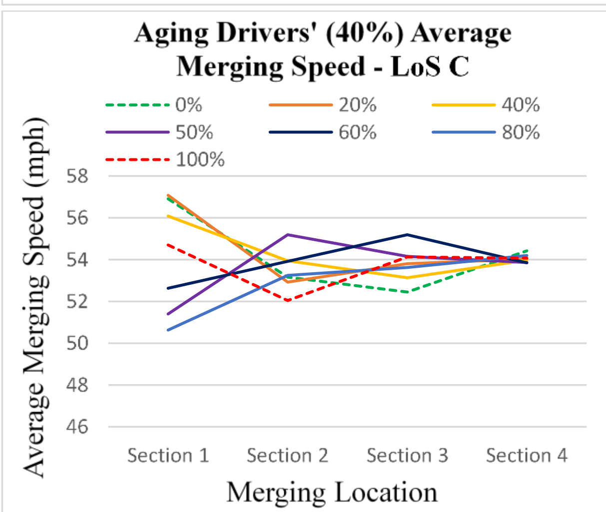
Appendix 9 - Average speed of older drivers during merging at Corkscrew entrance for various composition of aging drivers on-ramp for **LoS C**

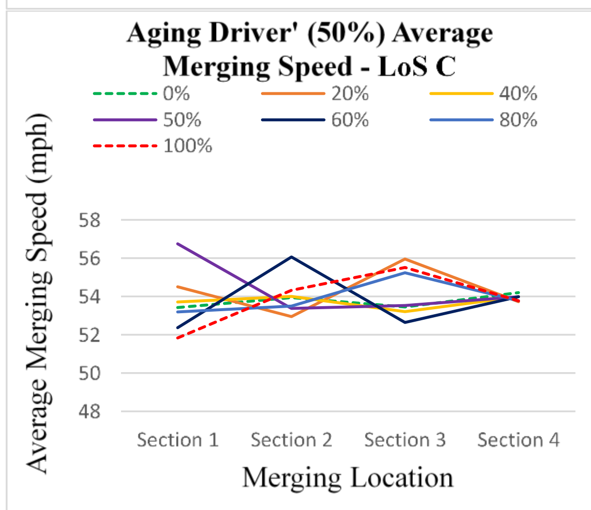




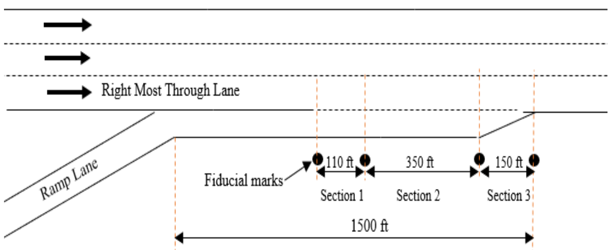


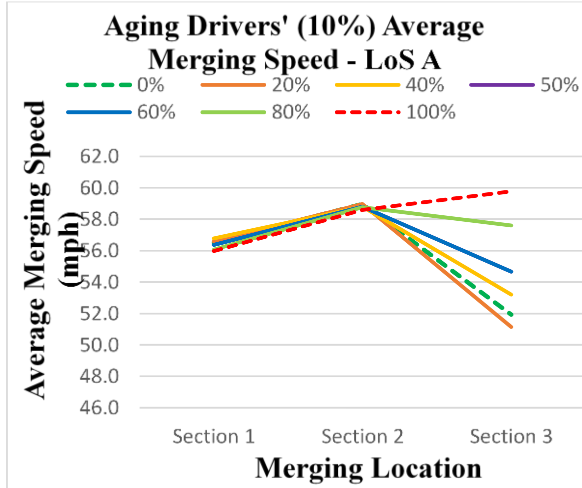


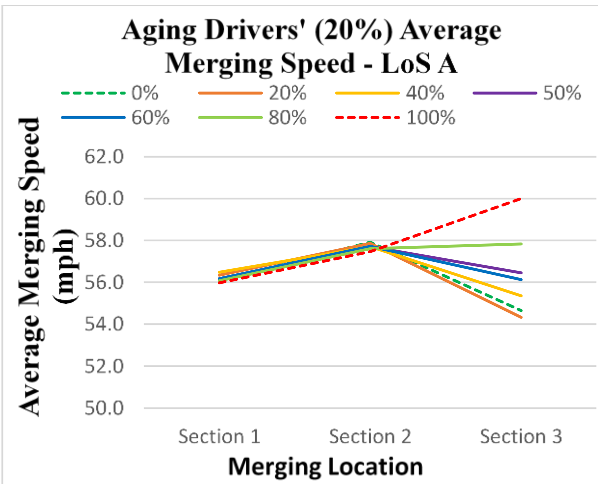


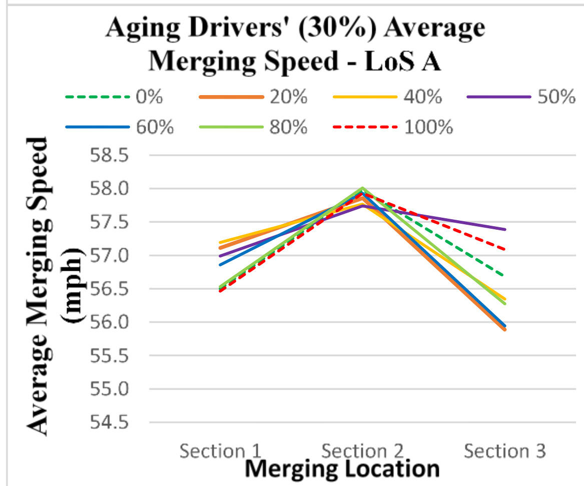


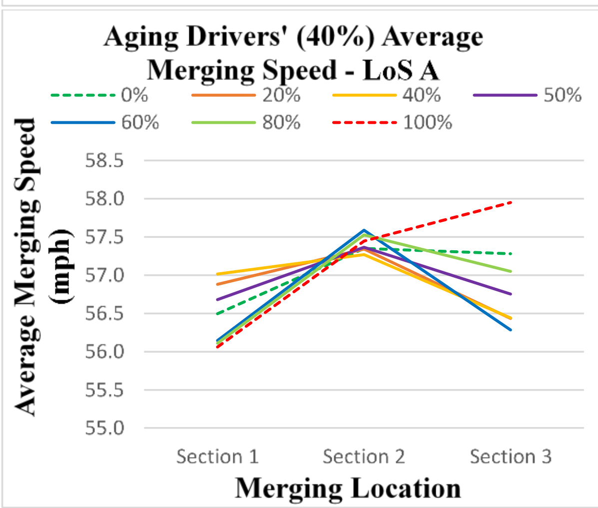
Appendix 10 - Average speed of older drivers during merging at Pine Ridge entrance for various composition of aging drivers on-ramp for **LoS A**

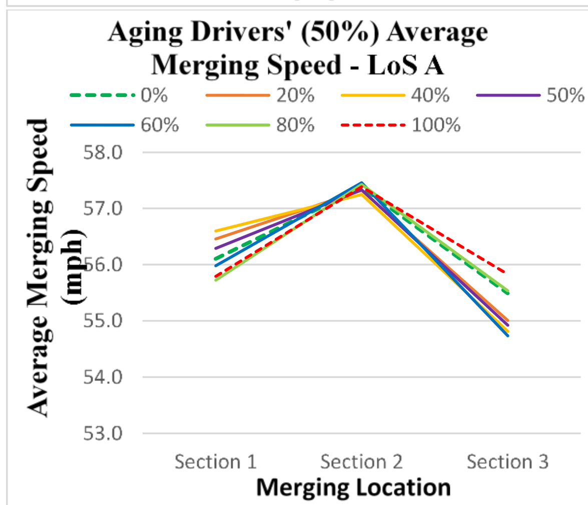




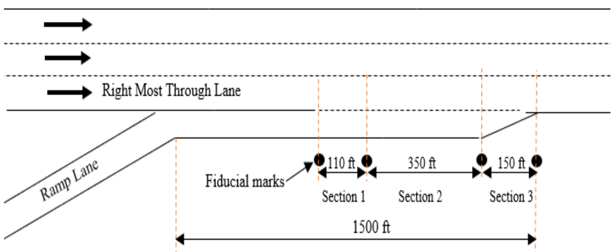


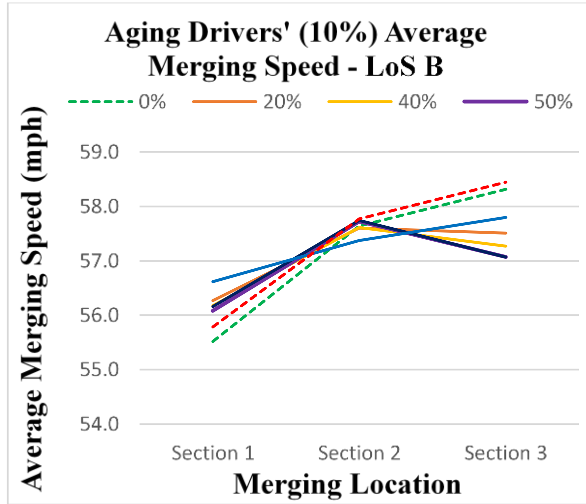


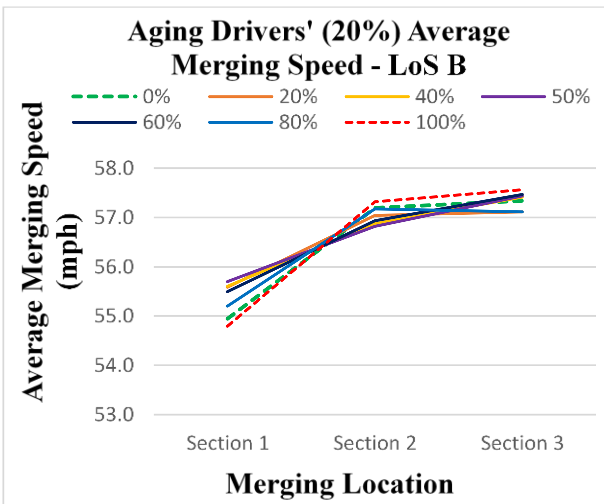


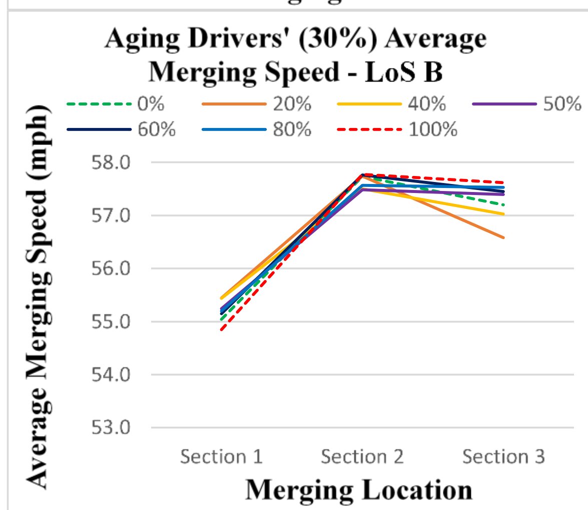


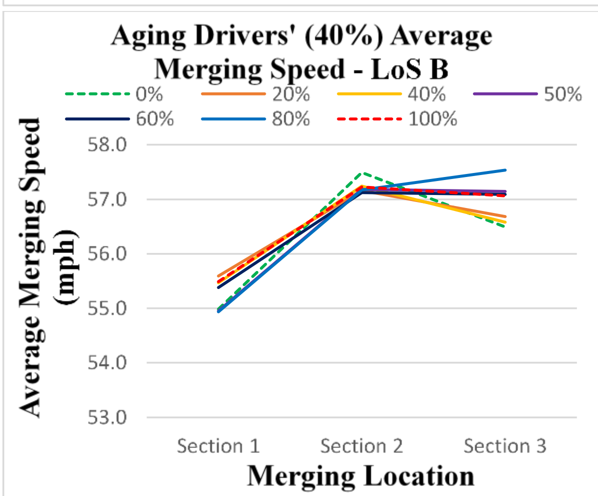
Appendix 11 - Average speed of older drivers during merging at Pine Ridge entrance for various composition of aging drivers on-ramp for **LoS B**

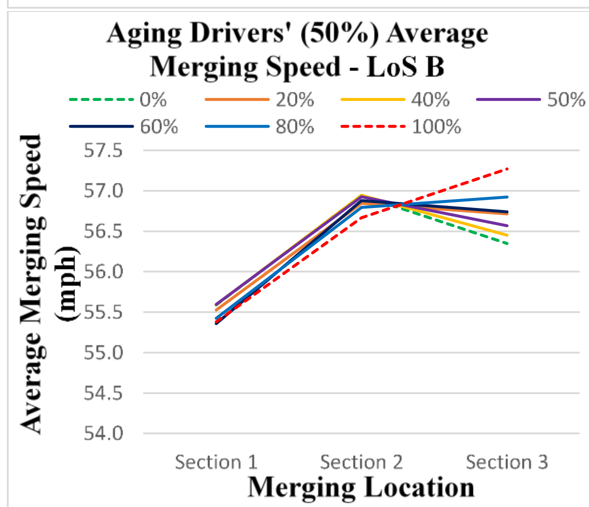




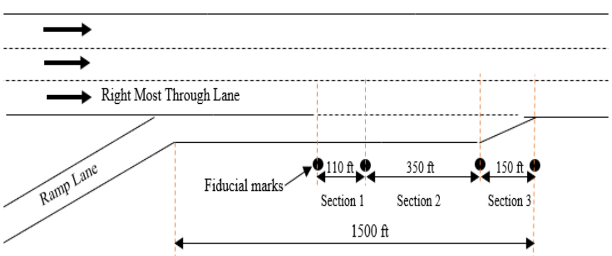


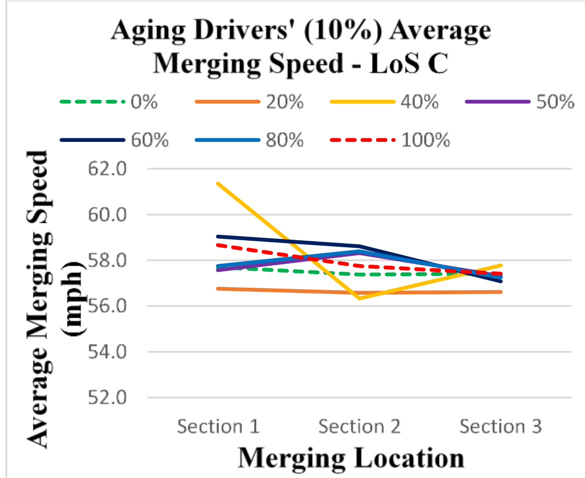


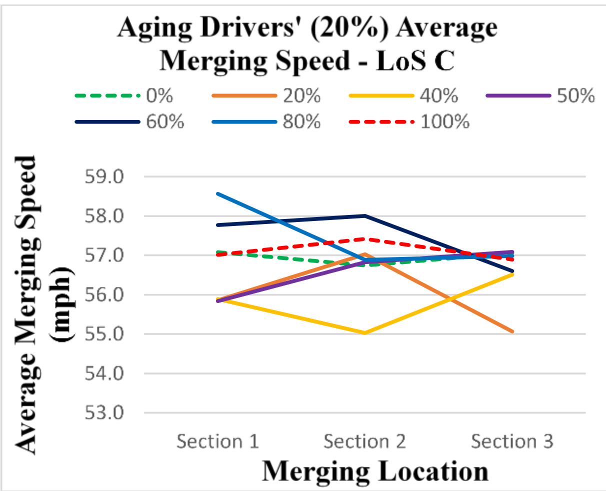


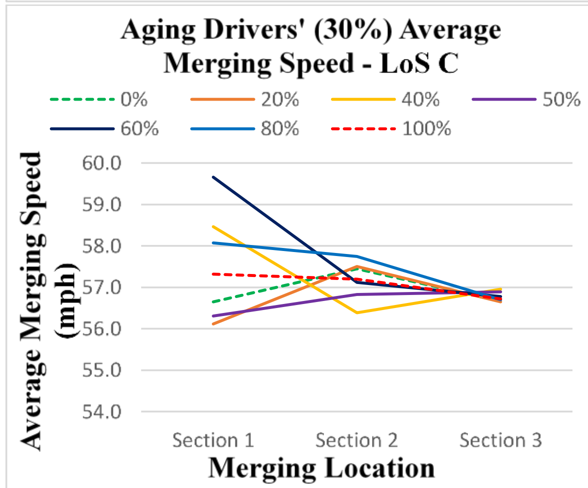


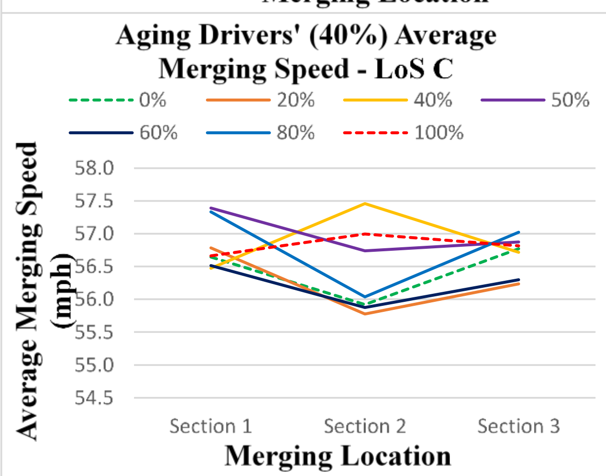
Appendix 12 - Average speed of older drivers during merging at Pine Ridge entrance for various composition of aging drivers on-ramp for **LoS C**

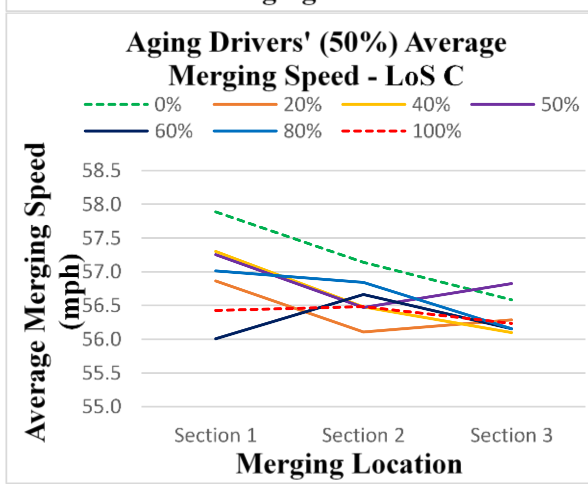












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