Center for Accessibility and Safety for an Aging Population

Florida State University

In Partnership with Florida A&M University and University of North Florida

RESEARCH FINAL REPORT

Developing an Algorithm using the Connected Vehicles Technology to Enhance Aging Drivers' Freeway Merging Maneuver – Phase I

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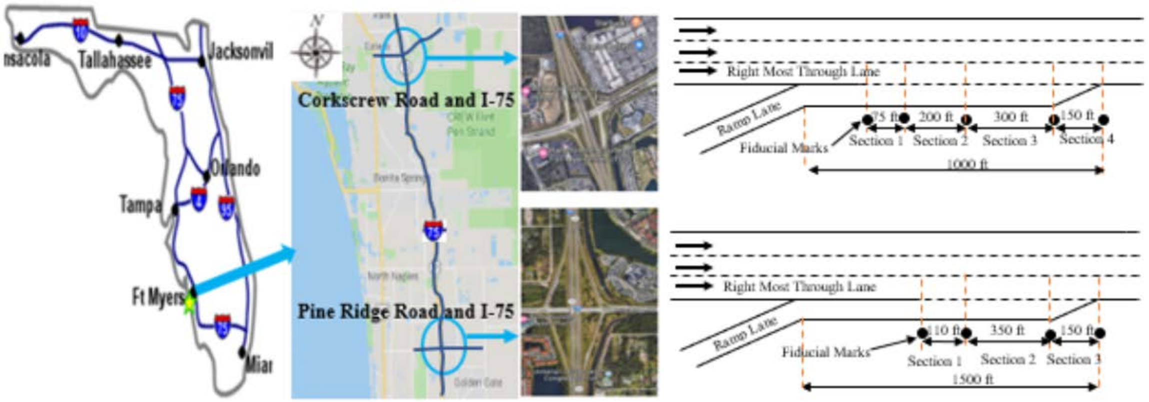

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A Report on Research Sponsored by

Center for Accessibility and Safety for an Aging Population

University of North Florida in Partnership with Florida A&M University

August 2019

Technical Report Documentation Page

<table>
<tr><td>1. Report No.</td><td colspan="2">2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="3" rowspan="2">4. Title and Subtitle
Developing an Algorithm using the Connected Vehicles Technology to Enhance Aging Drivers’ Freeway Merging Maneuver</td><td>5. Report Date
The date the report was received/published should appear here and on the title page, like June 2019</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="3">7. Author(s)
Thobias Sando (PI), Doreen Kobelo (Co-PI), Maxim Dulebenets (Co-PI)</td><td>8. Performing Organization Report No.
This is also where the WBS # appears</td></tr>
<tr><td colspan="3" rowspan="2">9. Performing Organization Name and Address
Center for Accessibility and Safety for an Aging Population
2525 Pottsdamer St., Suite A 129,
Tallahassee FL 32310</td><td>10. Work Unit No.</td></tr>
<tr><td>11. Contract or Grant No.</td></tr>
<tr><td colspan="3" rowspan="2">12. Sponsoring Agency Name and Address
Research and Innovative Technology Administration
1200 New Jersey Ave., SE
Washington, D.C. 20590</td><td>13. Type of Report and Period Covered
This is where the dates of the research appear, like June 2011-December 2011</td></tr>
<tr><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract
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<tr><td colspan="2">17. Key Words
Aging Drivers, Connected Vehicles, Cooperative Merging</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
59</td><td>22. Price</td></tr>
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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

ACKNOWLEDGEMENTS

This project was funded and administered by the Center for Accessibility for an Aging Population (ASAP) at the Florida State University, Florida A&M University and the University of North Florida. The opinions, results, and findings expressed in this manuscript are those of the authors and do not necessarily represent the views of ASAP or Florida State University, Florida A&M University and the University of North Florida.

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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 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 constructed 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 to determine how CMAS can enhance aging drivers' freeway merging maneuvers. The analysis involved 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 together with deceleration rate were the measures of effectiveness (MOEs) considered. The interaction states included braking for lane change, braking for emergency stop and braking to allow a vehicle from acceleration lane to merge (brake cooperative). Findings showed the number of aging drivers merging late onto the freeway decreased with CMAS, indicating mobility enhancement, while there was no variation in merging speed when CMAS was employed. The percentage reduction in late merges was greater at the longer acceleration lane than at the shorter acceleration lane; however, average speeds were nearly the same for all acceleration lane sections. Furthermore, the results show that CMAS reduced the percentages of aging drivers braking for lane change or stopping during freeway merging, as well as hard braking on acceleration lanes. Cooperative braking of mainline traffic was reduced at all levels of service. At 95% confidence level, the Mann-Kendall trend tests indicated that the reduction trends are significant. These interaction states used as surrogate safety measures signify that CMAS can enhance the safety of aging drivers with freeway merging maneuvers.

Key words: Aging Drivers, Connected Vehicles, Cooperative Merging

1.0 INTRODUCTION

1.1 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.

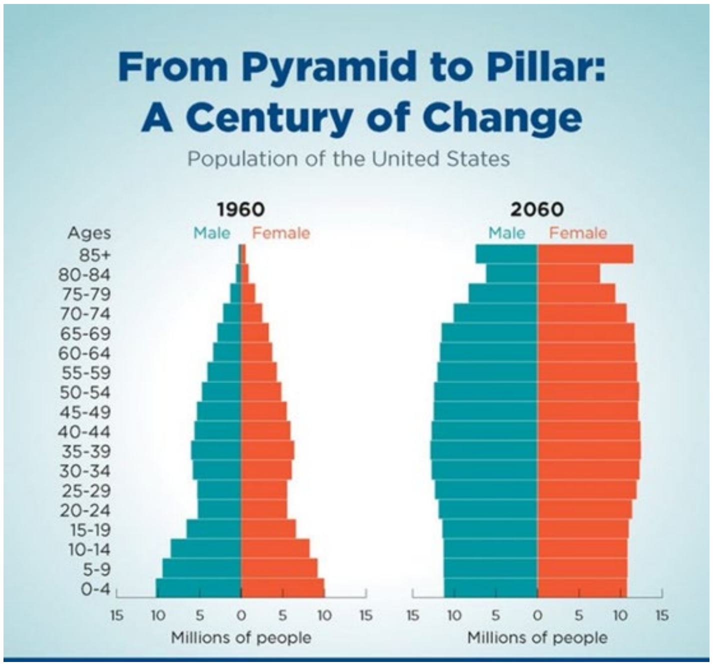


Figure 1.1: Projections of Population of the United States (Source: National Population Projections, 2017)

With this significant increase of older population, it’s so 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.

Older drivers do experience declining vision; slowed decision-making and reaction times; exaggerated difficulty 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 of 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 to accommodate merging vehicles, a wave is generated and can propagate upstream and lead to flow breakdown or perturbations. 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 technology has emerged as a potential option. The connected vehicles are used to communicate information about their speed and position. CV 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 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 to drivers during 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) 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 acceleration lane. It is obvious that a Cooperative Merging Assistance System is safe compared with human operations alone.

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

This study is preceded by a study that modeled the behavior of aging on-ramp drivers. In this study, Vissim software was used as a microscopic simulation tool. Merging location, merging speed and aging driver interaction states together with deceleration rates (hard braking) were used as Measures of Effectiveness (MOEs) for evaluating the performance of CMAS.

2.0 LITERATURE REVIEW

The population in the United States (U.S.) is aging. The American Community Survey Report estimated the number of people aged 65 and over in the U.S as 49.2 million in 2016. (Roberts et al., 2018). The 65 and older population in Florida is expected to reach 20% of the state's total population this decade (Safety Mobility for Life Coalition, 2018). Consequently, an increase in aging drivers is anticipated with an aging population.

Driving is associated with several tasks. These tasks are performed either in quick succession or simultaneously where drivers must react to a number of vehicular parameters, other motorists, and pedestrian behaviors, as well as varying weather conditions, road geometry, and surface conditions, all of which are vital to perform the driving task safely (Hulse, Xie, & Galea, 2018). These complexities of driving may be more difficult for older drivers who may experience challenges associated with aging, such as diminished sensory, perceptual, and cognitive abilities (Laosee, Rattanapan, & Somrongthong, 2018).

Driver age has an effect on traffic performance measures and safety (Ulak, Ozguven, Moses, Abdelrazig, & Sando, 2018). For example, for every decade after age 25, drivers need twice the brightness at night to receive visual information (AASHTO, 2011). Hence, by age 75, some drivers may need 32 times the brightness they did at age 25. In comparison to young drivers, older drivers are more at risk due to frailty. They also have less agility judging time, with slower reaction times increasing the risk of crashing (Chevalier et al., 2016). In 2013, older drivers attributed to 17 percent of all traffic fatalities and 10 percent of all injuries resulting from traffic crashes in the U.S. (NHTSA, 2015).

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, Eustace, Chimba, & Qumsiyeh, 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, Martens, & Moerdijk, 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.

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.

Connected vehicle (CV) technology is among the ITS strategies that aid drivers with traffic operations, such as merging maneuvers. Information, such as vehicle speed and position, can be communicated through CVs and support various traffic management efforts to improve traffic operations on roadway networks. Capacity can also be increased in existing networks when utilizing CV technology as a system-wide ITS strategy (Jadaan et al., 2017). CVs possess a cooperative behavior which allows each vehicle to recognize the intentions and positions of other vehicles (Radu Popescu-Zeletin & Rigani, 2010), and CV technology can support various ITS applications, such as cooperative merging (Scarinci et al., 2017).

Wireless communication between vehicles contributes to the safety of road users (Lu, Cheng, Zhang, Shen, & Mark, 2014). These communications enhance the reliability of driving operations as driver perception of the driving environment is improved (Talebpour & Mahmassani, 2015) by not only assisting on-ramp drivers with finding an acceptable gap to merge, but also helping the mainline drivers with acceleration-deceleration decisions before providing a gap for a merging vehicle (Milanes, Godoy, Villagra, & Perez, 2011). Since connected vehicles can communicate in a wireless environment, cooperative merging assistance systems can enhance safety (Radu Popescu-Zeletin & Rigani, 2010; Scarinci et al., 2017; Scarinci & Heydecker, 2014). Knowledge of the extent of these systems in facilitating safe operations is of utmost importance.

Cooperative merging can be used to compensate for the deficiencies that older drivers may possess and add to their ability to perform merging maneuvers. Systems that support cooperative merging are proactive, cooperative, and coordinate information (Lu et al., 2014). Cooperative Merging Assistance (CMA) systems utilize emerging technologies to address the limitations of ramp metering to facilitate the merging process (Scarinci et al., 2017). CMA modifies the gaps between vehicles on the freeway without significantly changing the vehicles' speed, and combines shorter headways into longer headways to enhance merging maneuvers (Scarinci, Heydecker, & Hegyi, 2015). The system provides a safer, automatic method for a vehicle to merge with flowing traffic (Radu Popescu-Zeletin & Rigani, 2010). CMA also assists drivers with lane changing maneuvers by creating and maintaining an appropriate gap in the target lane (Tampere, Hogema, Katwijk, & Van Hem, 1999). A CMA system for on-ramps can utilize intelligent vehicles capable of V2I (vehicle-to-infrastructure) communication (Scarinci et al., 2017).

The effectiveness of certain traffic control strategies can be tested using simulation methods, which mimic actual traffic conditions (Sarvi, Kuwahara, & Ceder, 2004). Microscopic traffic simulation models provide an important tool for Traffic Engineers in the analysis and management of transportation systems (Hidas, 2002). These models are also capable of reproducing acceleration lane scenarios (Cantisani, Serrone, & Biagio, 2018). In simulations of freeway merging maneuvers, an essential component in all microscopic simulation models is the oscillation (acceleration-deceleration) characteristics of merging vehicles in the acceleration lane (Sarvi et al., 2004).

3.0 METHODOLOGY

3.1 Model Building

As an extension of the previous ASAP work on merging behavior, the current work utilizes the models created as base models. Two models of the study 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 details on the calibration and validation on the model can be obtained in (Lwambagaza, 2016).

3.1.1 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.

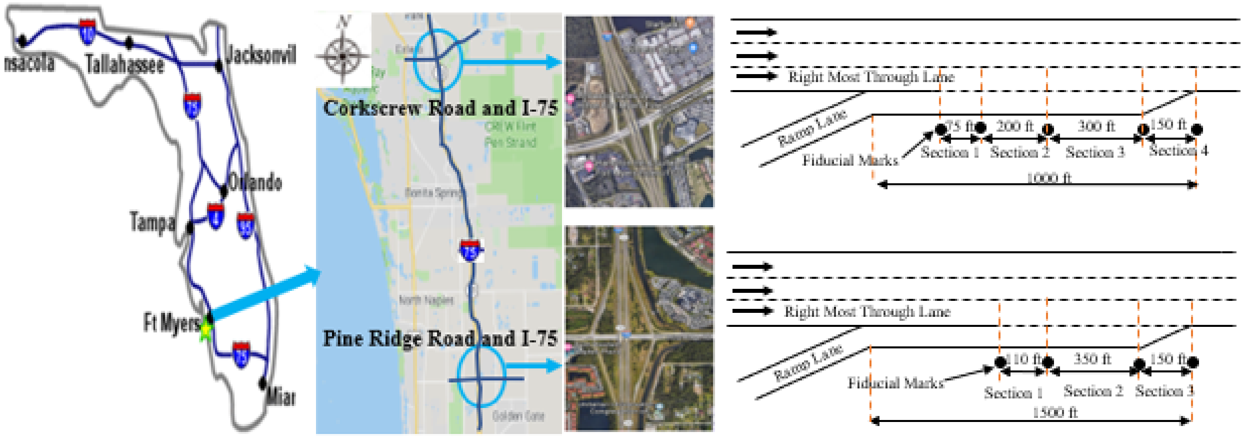


Figure 3.1: Map and shematic of I-75 on-ramps at Corkscrew Road and Pine Ridge Road (Source: Google Earth, 2019) (Not to scale)

3.1.2 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**	**O**	**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

Where by: 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.

3.1.3 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 how the merging area should be 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

3.2 Development of Merging Algorithm

The merging algorithm has several steps during its execution. The steps consider the provision of enough gap for safety purpose during merging.

3.2.1 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).

3.2.2 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).

3.2.3 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 difference was selected and the one with the smallest absolute time difference was considered as the starting point for adjusting speed. $\pm 3s$ was used because the recommended safety following distance is 4s. 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.

3.2.4 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.

3.2.5 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, all vehicles behind lagging vehicle, including the lagging vehicle decelerate.

3.2.6 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.

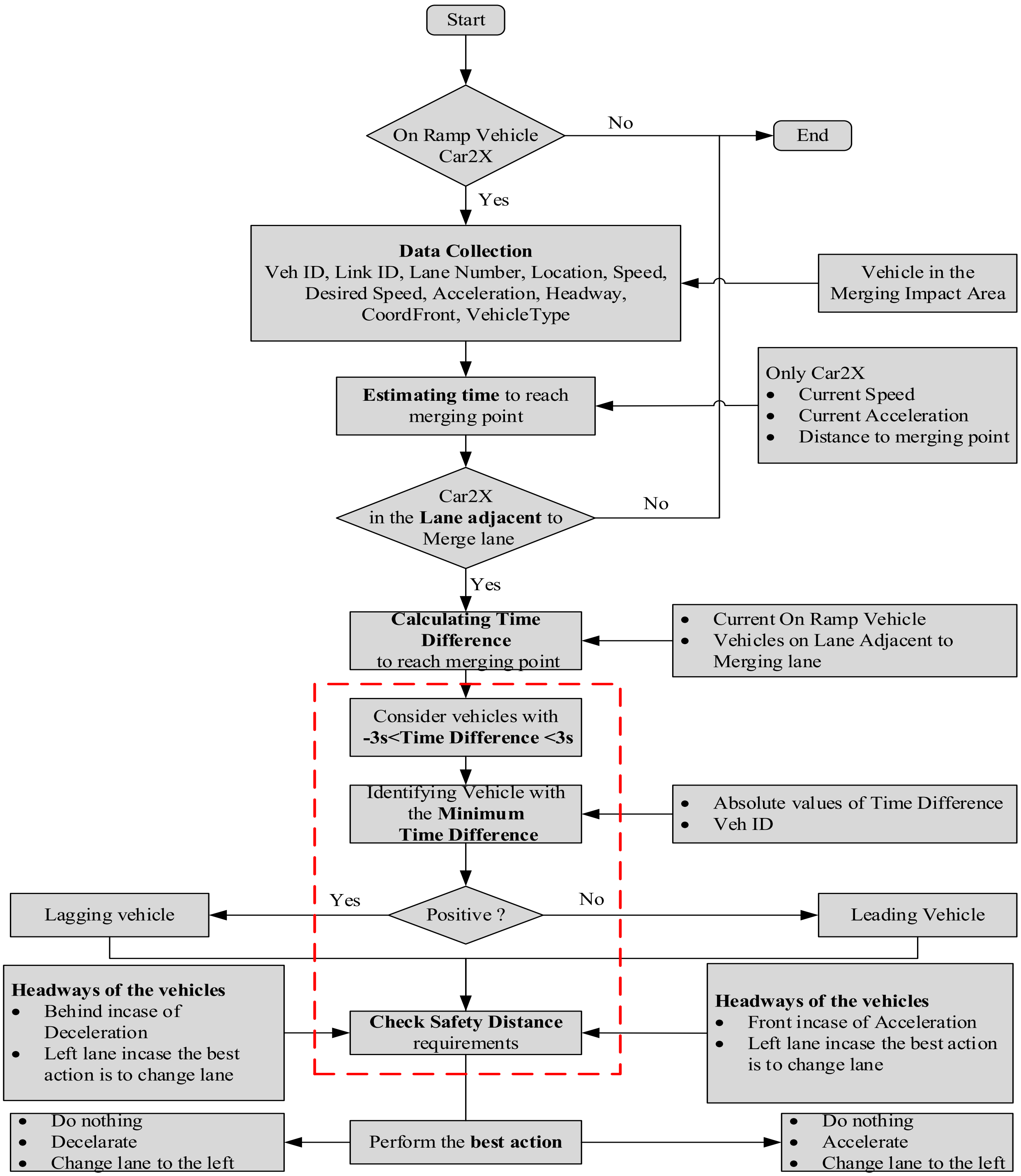


Figure 3.4: Logic Flow Chart of the CMAS Algorithm

3.3 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.

The sensitivity analysis was conducted for 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). 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.

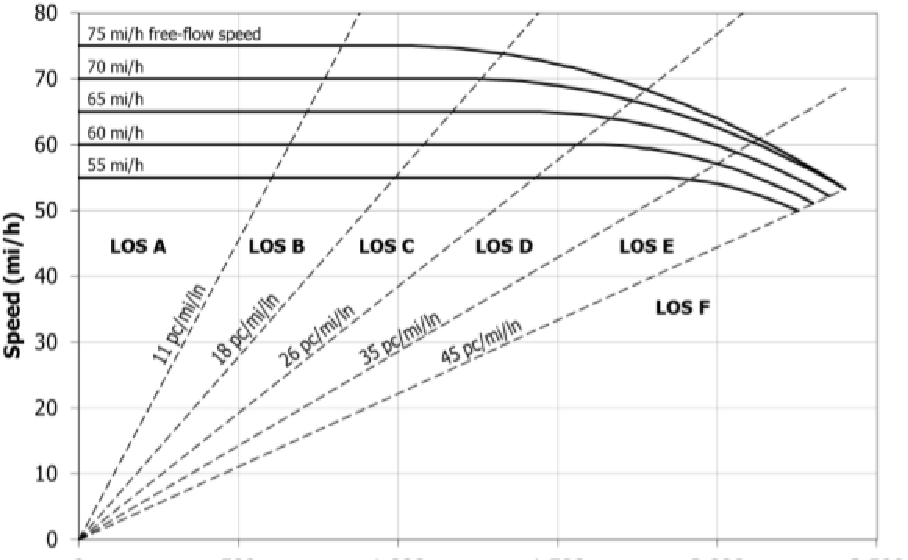


Figure 3.5: LoS Criteria and Speed-Flow Curves for Basic Freeway Segements (Source: Highway Capacity Manual, 2016)

3.3.1 Measures of Effectiveness

Sensitivity analysis was conducted in Vissim for 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. 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 (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 (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.

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. Braking for emergency stop refers to a vehicle that has failed to merge onto the mainline within the limits of the acceleration lane and must stop before attempting to merge.

4.0 RESULTS AND DISCUSSIONS

The acceleration lanes at each study site were divided into several sections. Four sections were identified at the Corkscrew Road Entrance, Figure 4.1, and three acceleration lane sections were identified at the Pine Ridge Road Entrance Figure 4.2.

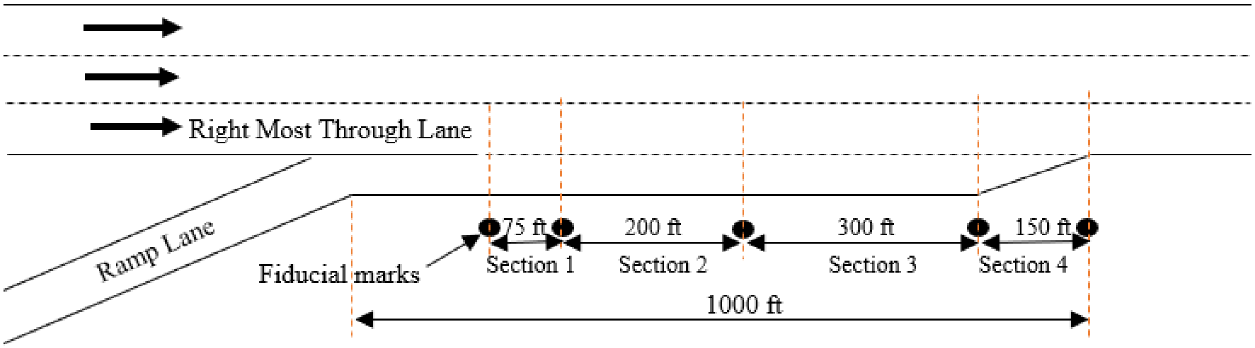


Figure 4.1: On-Ramp Geometry -I-75 at Corkscrew Road (Not to Scale)

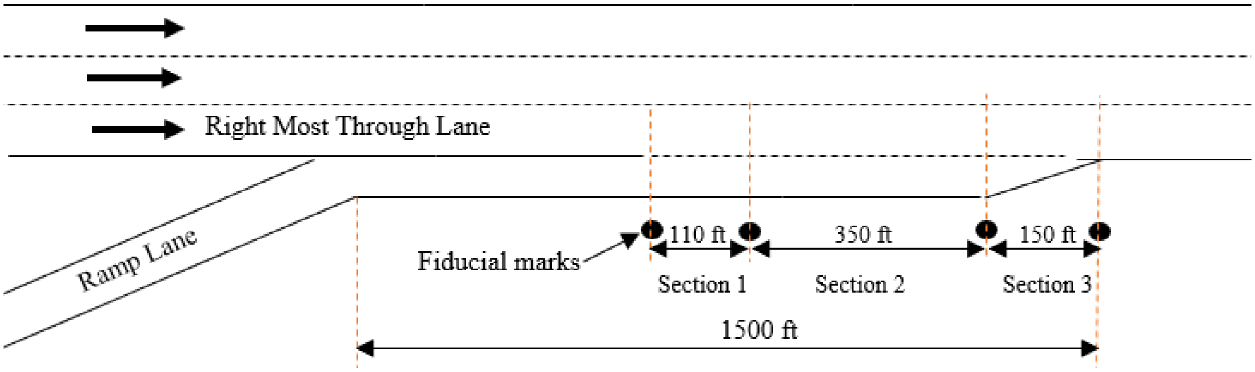


Figure 4.2: On-Ramp Geometry -I-75 at Pine Ridge Road (Not to Scale)

4.1 Merging Location

Figures 5.3 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. Table 4.1 provides the percentage reduction in late merges for Corkscrew and Pine Ridge entrances with a 100% CV penetration rate, i.e., when all vehicles in the mainline and on-ramp are connected vehicles. 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.

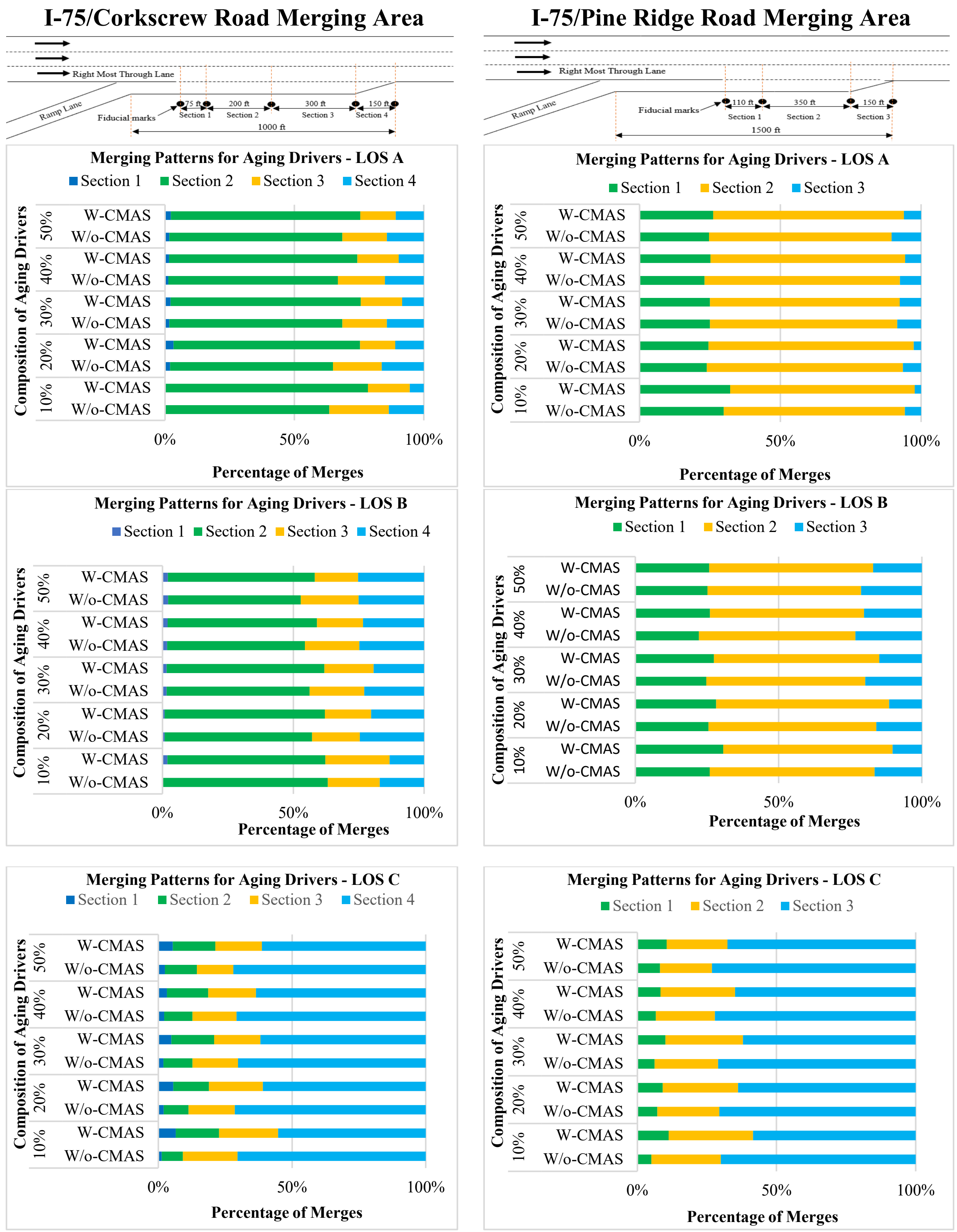


Figure 4.3: Merging patterns of aging on-ramp drivers (with and without CMAS)

Table 4.1: 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%	60.00%	60.00%
	20%	60.00%	32.00%
	30%	10.00%	41.18%
	40%	23.77%	35.42%
	50%	41.72%	24.14%
B	10%	38.10%	22.22%
	20%	26.93%	17.59%
	30%	24.93%	15.69%
	40%	13.17%	5.79%
	50%	19.83%	-0.95%
C	10%	16.60%	21.59%
	20%	9.52%	15.13%
	30%	14.30%	11.88%
	40%	9.97%	10.28%
	50%	7.64%	14.92%

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.

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%, 38.10%, and 16.60%, while at the shorter acceleration lane the percentage reductions were 60%, 22.22%, and 21.59% 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 41.72%, 19.83%, and 7.64% at the longer acceleration lane, while at the shorter acceleration lane, the percentage reductions were 24.14%, -0.95%, and 14.92% for LOS A, B, and C, respectively. 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% to 10% at LOS A, 38.10% to 13.17% at LOS B, and 16.60% to 7.64% at LOS C, with standard deviations of 22.15%, 9.24%, and 3.71% for LOS A, B, and C respectively. At the shorter acceleration lane, the percentage reductions were between 60% to 24.14% at LOS A, 22.22% to -0.95% at LOS B, and 21.59% to 10.28% at LOS C, with standard deviations of 13.48%, 9.43%, and 4.34% 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.

4.2 Merging Speed

Figures 4.4 and Table 4.2 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 4.4: Average merging speed of aging on-ramp drivers (with and without CMAS)

Table 4.2: 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		52.53	53.46	56.28		56.52	58.97	51.93
	With CMAS		52.51	55.47	57.31		55.97	58.59	59.77
20%	Without CMAS	41.40	51.89	53.70	55.56		56.07	57.92	54.65
	With CMAS	41.12	52.09	54.77	55.91		55.97	57.47	60.00
30%	Without CMAS	41.20	52.11	55.31	54.05		56.50	57.98	56.68
	With CMAS	42.51	51.86	57.30	54.51		56.46	57.93	57.09
40%	Without CMAS	41.20	52.44	54.97	55.18		56.50	57.35	57.28
	With CMAS	40.68	52.28	56.86	55.76		56.06	57.45	57.95
50%	Without CMAS	41.61	53.07	53.84	55.61		56.10	57.38	55.49
	With CMAS	42.85	52.61	56.87	56.19		55.79	57.38	55.83
		Average Merging Speed (mph) of Aging On-Ramp Drivers at LOS B							
10%	Without CMAS		52.81	52.14	57.59		55.52	57.64	58.31
	With CMAS	44.81	51.77	56.57	56.91		55.78	57.77	58.45
20%	Without CMAS	38.22	52.57	51.78	54.35		54.94	57.20	57.34
	With CMAS	41.88	51.48	54.26	55.70		54.79	57.32	57.56
30%	Without CMAS	45.73	53.14	52.65	54.32		55.04	57.73	57.20
	With CMAS	46.95	52.42	54.97	54.34		54.85	57.77	57.62
40%	Without CMAS	45.63	53.14	53.44	54.35		54.99	57.49	56.50
	With CMAS	47.29	52.14	55.28	55.39		55.49	57.22	57.06
50%	Without CMAS	47.61	52.96	53.76	54.72		55.59	56.95	56.35
	With CMAS	48.74	52.34	54.21	55.77		55.38	56.67	57.27
		Average Merging Speed (mph) of Aging On-Ramp Drivers at LOS C							
10%	Without CMAS	58.56	52.22	51.20	54.03		57.70	57.38	57.42
	With CMAS	50.99	52.43	55.48	52.93		58.67	57.75	57.41
20%	Without CMAS	47.77	53.54	51.83	53.33		57.08	56.75	57.06
	With CMAS	52.45	52.89	54.29	53.48		57.01	57.42	56.90
30%	Without CMAS	53.26	53.66	53.33	53.88		56.65	57.44	56.66
	With CMAS	52.89	55.06	54.13	53.18		57.32	57.20	56.72
40%	Without CMAS	56.90	53.15	52.45	54.42		56.65	55.92	56.77
	With CMAS	54.69	52.04	54.13	54.07		56.66	57.00	56.81
50%	Without CMAS	53.43	53.95	53.45	54.20		57.89	57.14	56.58
	With CMAS	51.83	54.33	55.52	53.77		56.43	56.48	56.23

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).

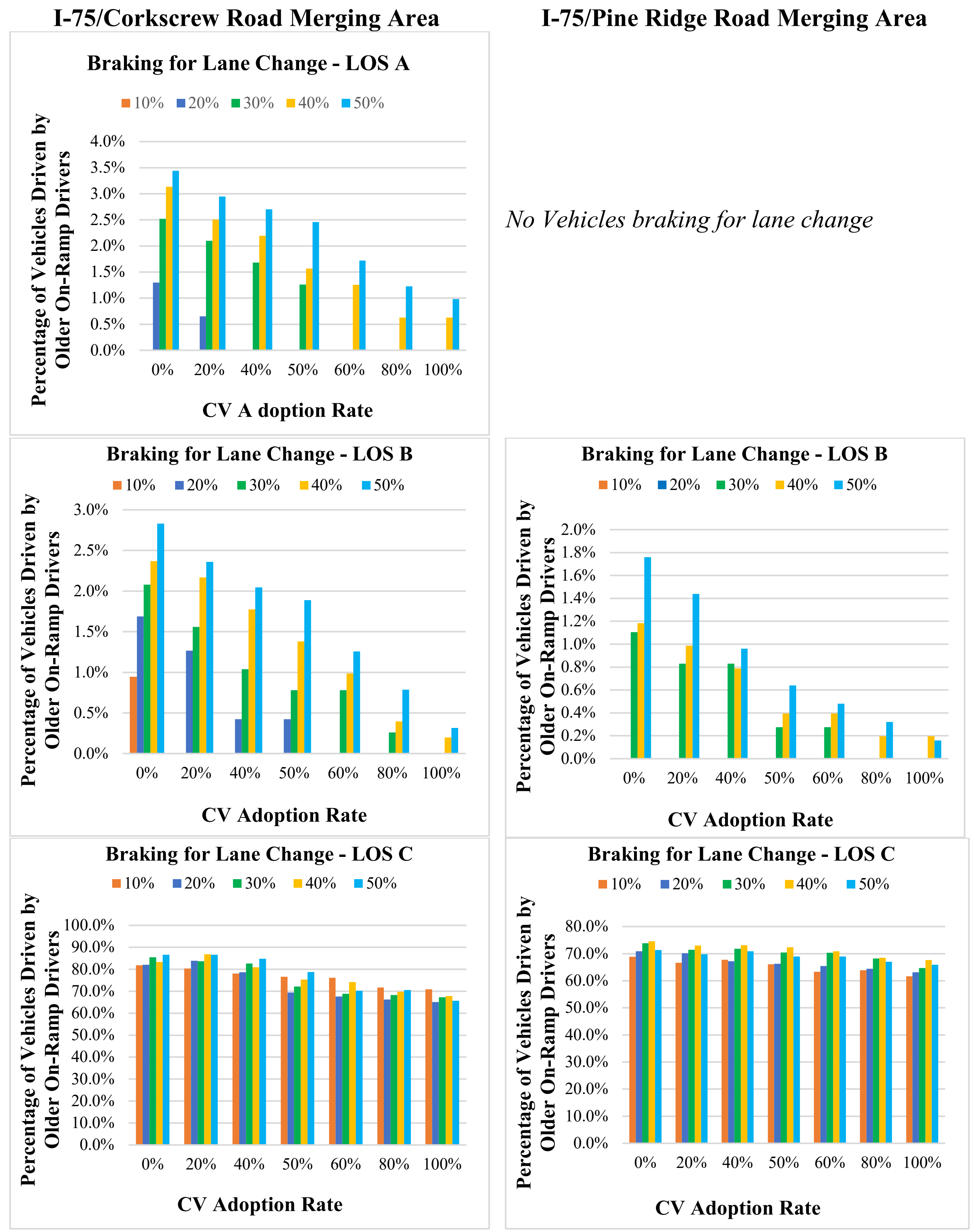
4.3 Vehicle Interaction States

The VISs in the vehicle record files extracted from VISSIM provide information on the operations of vehicles at different locations in the modeled freeway merging areas. Table 4.3 provides a description of the interaction states used in this study.

Table 4.3: 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

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 4.5, while Figure 4.6 shows the percentage of vehicles driven by aging drivers braking for an emergency stop during the freeway merging maneuver. Figure 4.7 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 4.8 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.



I-75/Corkscrew Road Merging Area

I-75/Pine Ridge Road Merging Area

No Vehicles braking for lane change

Figure 4.5: Braking for lane change by aging drivers on acceleration lane

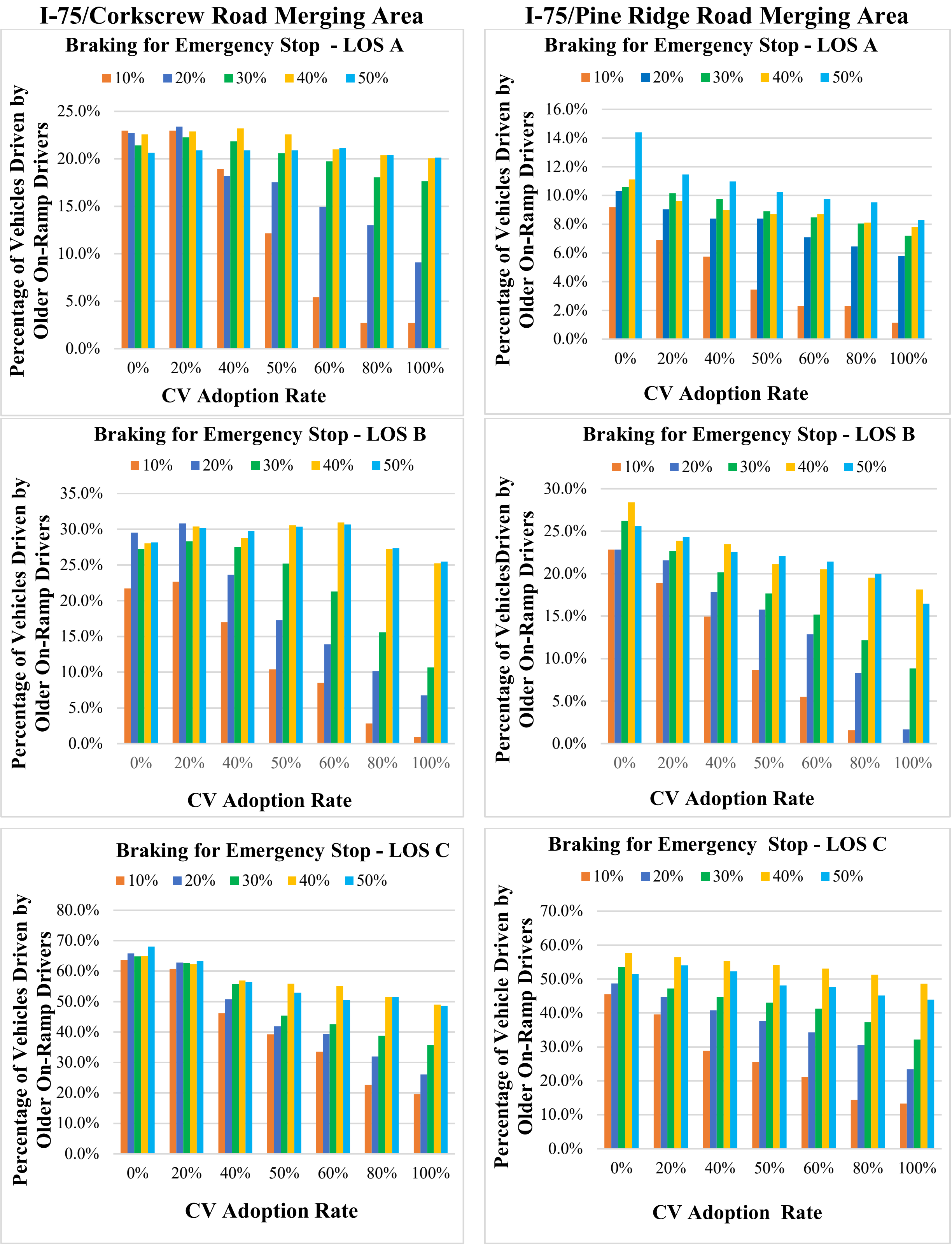


Figure 4.6: Braking for emergency stop by aging drivers on acceleration lane

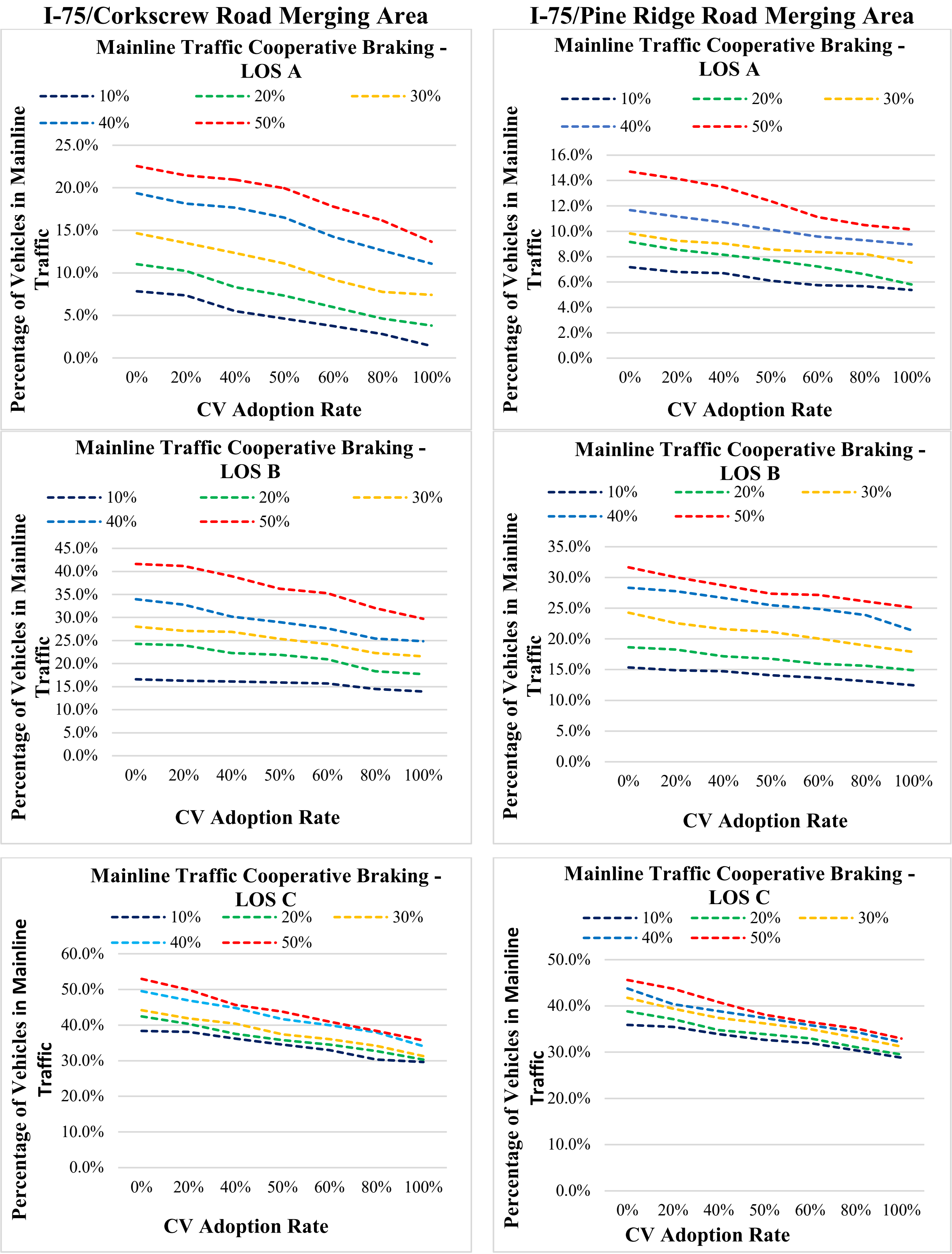


Figure 4.7: Brake cooperative for mainline traffic in the right most through lane

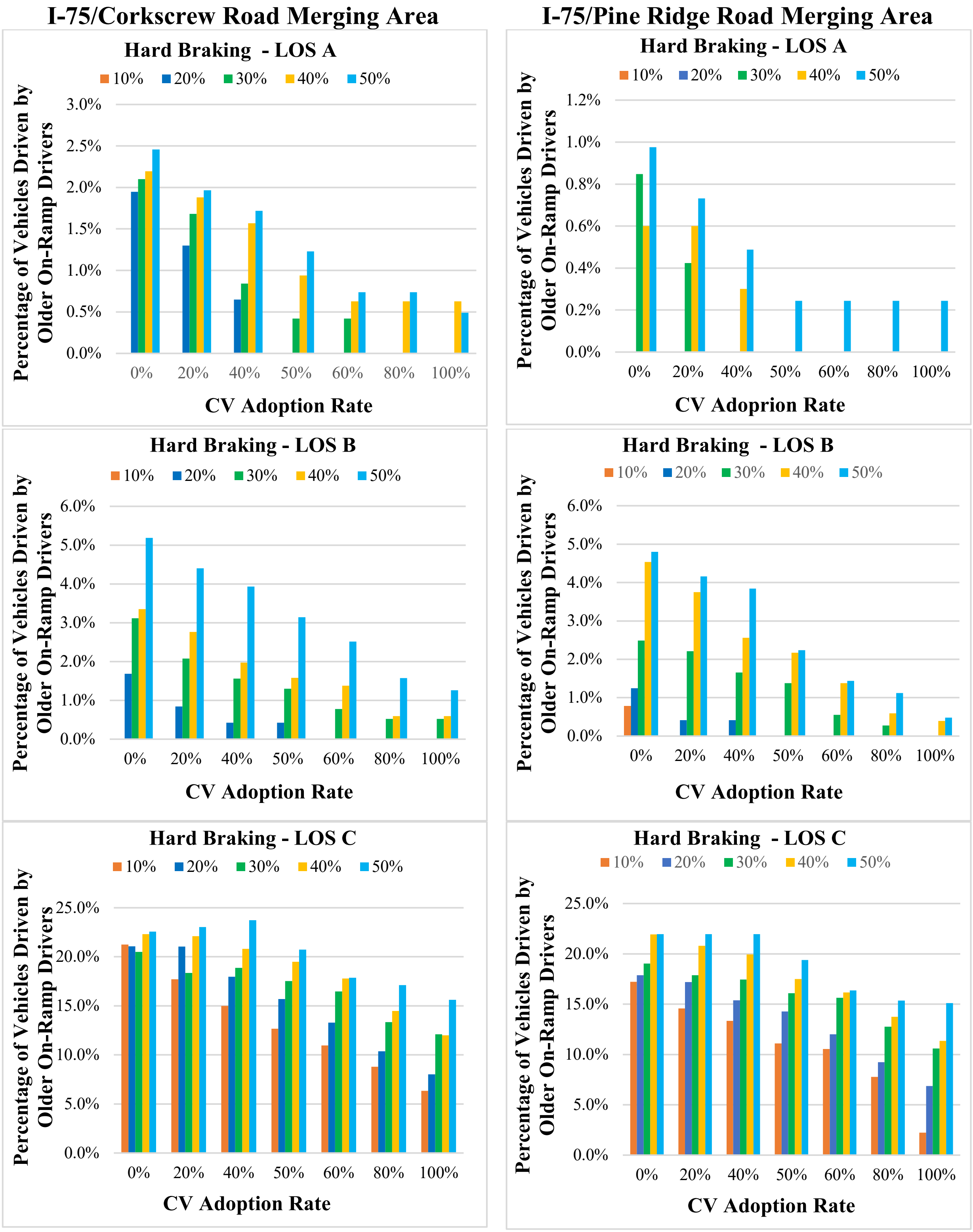


Figure 4.8: Hard braking by aging drivers on acceleration lane

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 ($14.8 ft/s^2$) (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. 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. 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. 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.

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 4.6%) for the longer acceleration lane, while the standard deviation of percentage reduction for the shorter acceleration lane was 17.59%. 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.

4.3.1 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) that there was no trend in the series, and the alternative hypothesis (H_a) that a trend was present in the series. Table 4.4 provides the results obtained from the Mann-Kendall test statistic for the VISs at different aging driver compositions.

Table 4.4: Results of Mann-Kendall trend test for aging driver 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

About 120 trend tests were conducted; however, 12 tests were not possible to conduct as the sequences were constant (0.00%). For the 108 Mann-Kendall trend tests performed, there was not enough evidence to reject the null hypothesis for seven 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.

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 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.

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.

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 (at least 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 traffic demand (LOS A), the average reduction rate was 47.07% at the longer acceleration lane location compared to 35.89% 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 66.14% to 50.62%, while the pattern changed with higher traffic demand (LOS C), where the reduction rate was 38.62 % for the longer acceleration lane compared to 45.55% 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 4.6%) for the longer acceleration lane, while the standard deviation of percentage reduction for the shorter acceleration lane was 17.59%.

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.

Study limitations

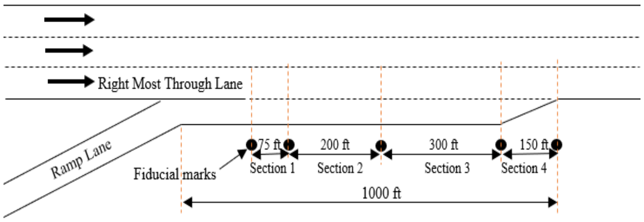
This study assumed that all connected vehicles obeyed the messages they received when in the merging area. Furthermore, the study assumed the effect of traffic operations on the mainline traffic in the merging area was limited to the merging vehicles, which is not always the case. Other limitations include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

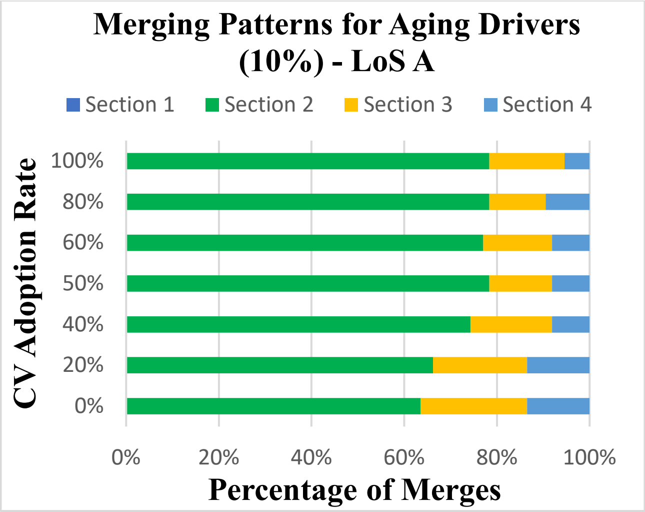
5.2 Recommendations for future work

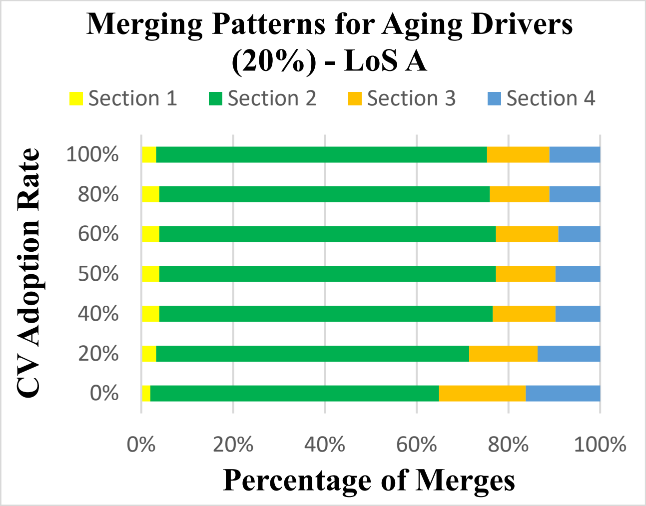
Further analysis is needed on the effects of traffic operations using other age groups of drivers to evaluate freeway merging maneuvers with and without CMAS. More interaction states can also be incorporated to expand the analysis to all driver age groups on acceleration lanes, as well as those in the 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 simulation 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.

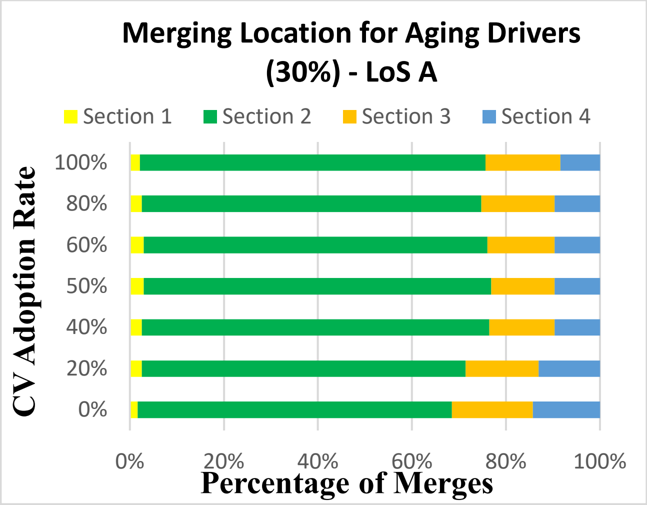
APPENDICES

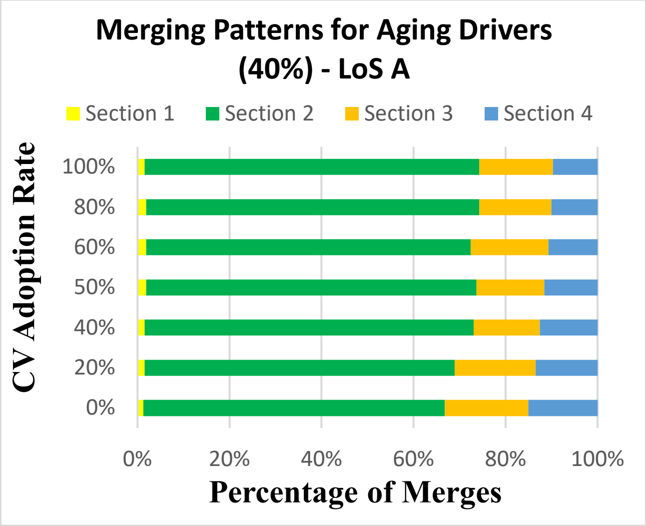
Appendix 1 – Merging patterns at Corkscrew entrance for various aging drivers' composition on-ramp for **LoS A**

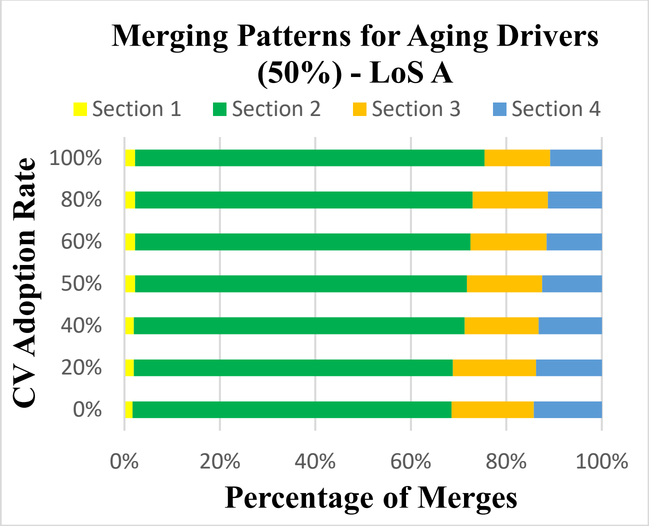




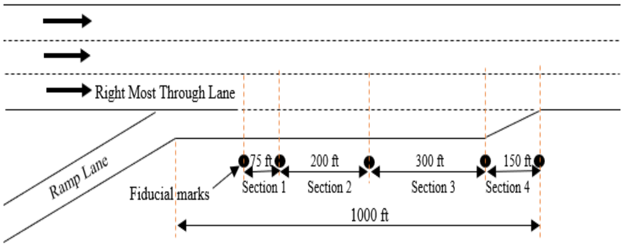


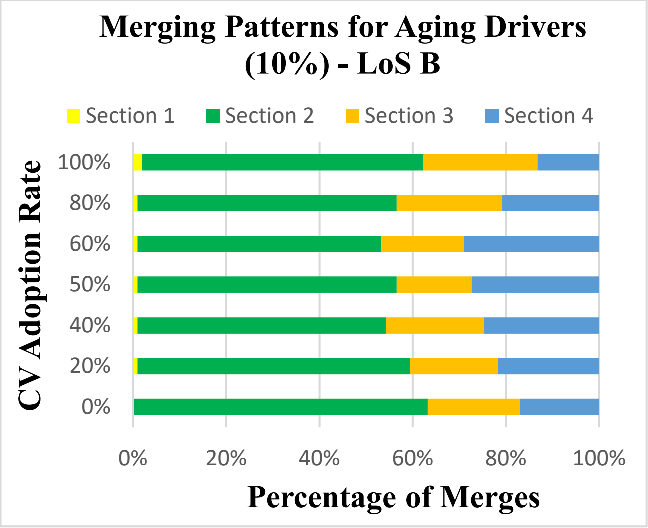


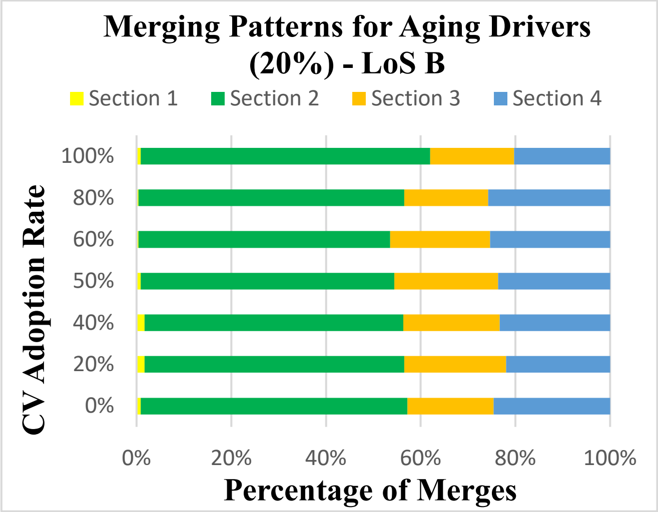


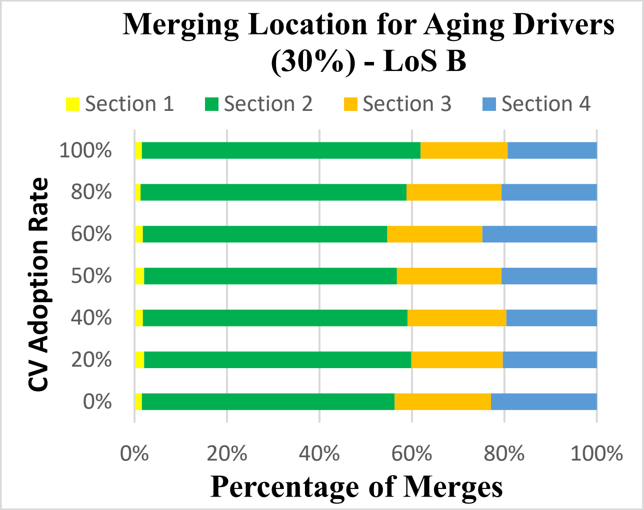


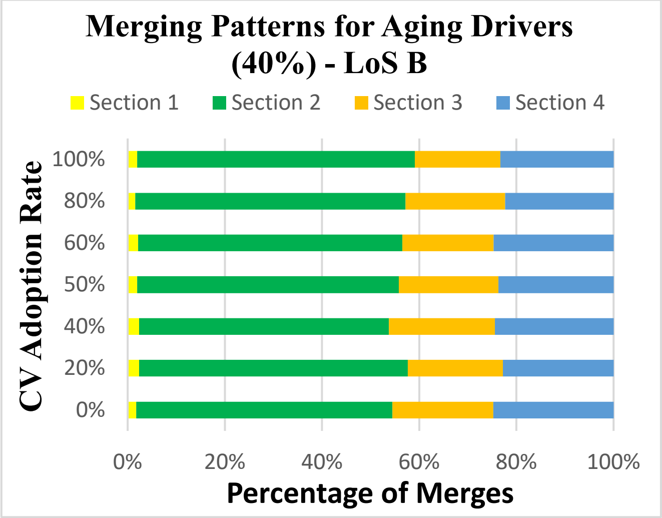
Appendix 2 – Merging patterns at Corkscrew entrance for various aging drivers' composition on-ramp for **LoS B**

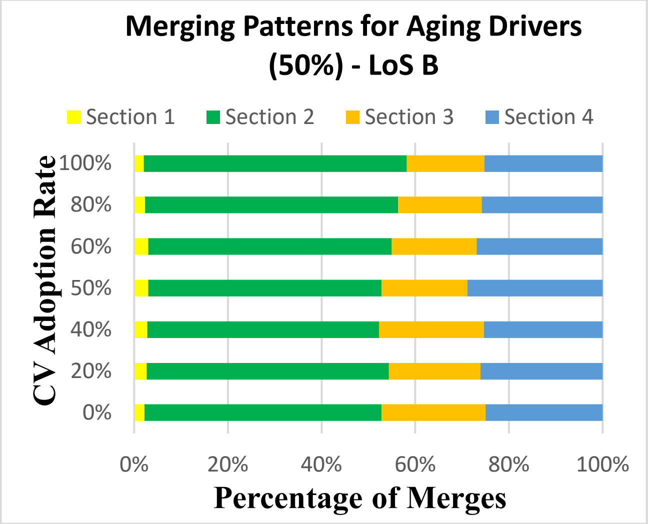




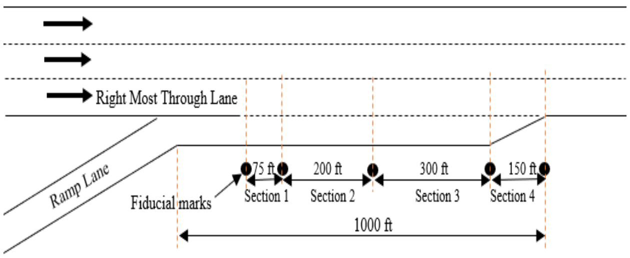


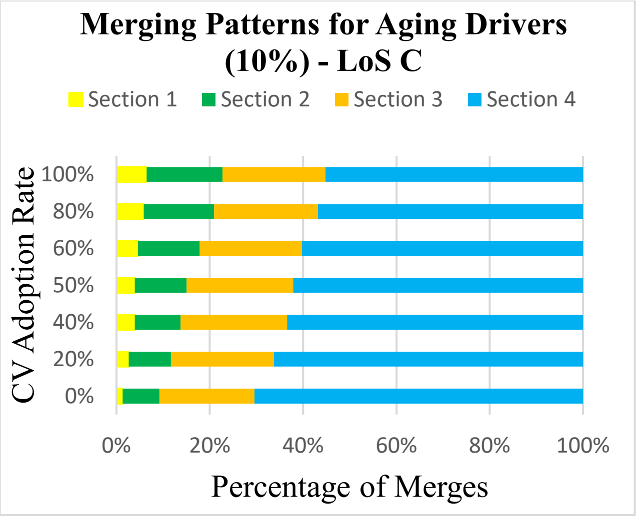


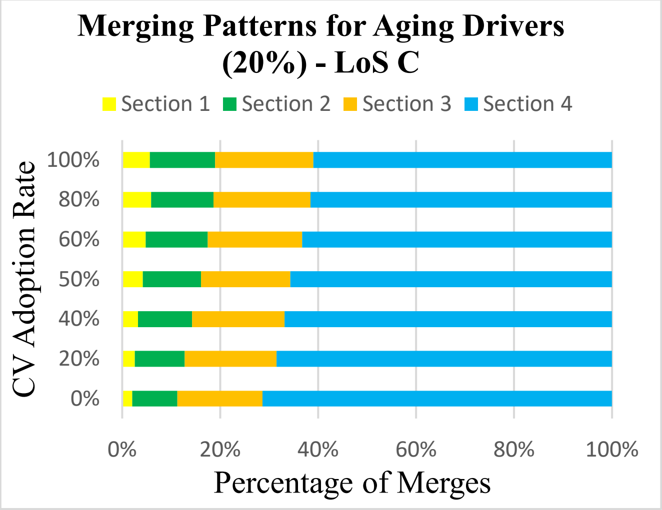


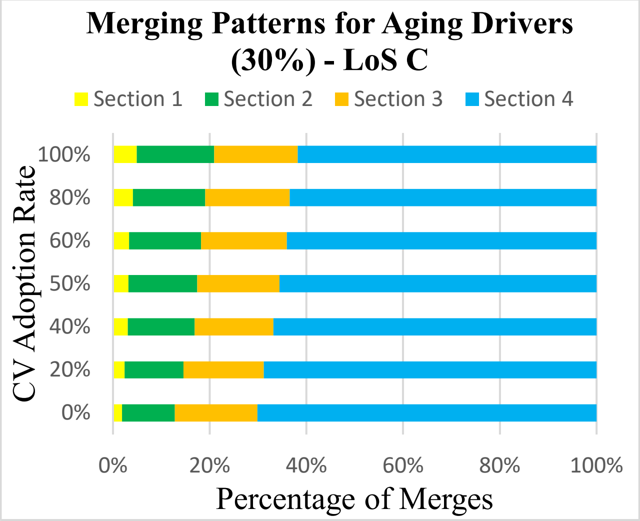


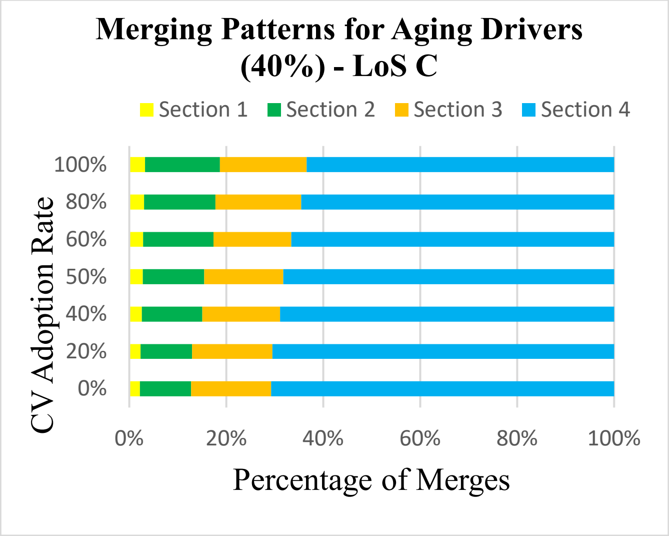
Appendix 3 – Merging patterns at Corkscrew entrance for various aging drivers' composition on-ramp for **LoS C**

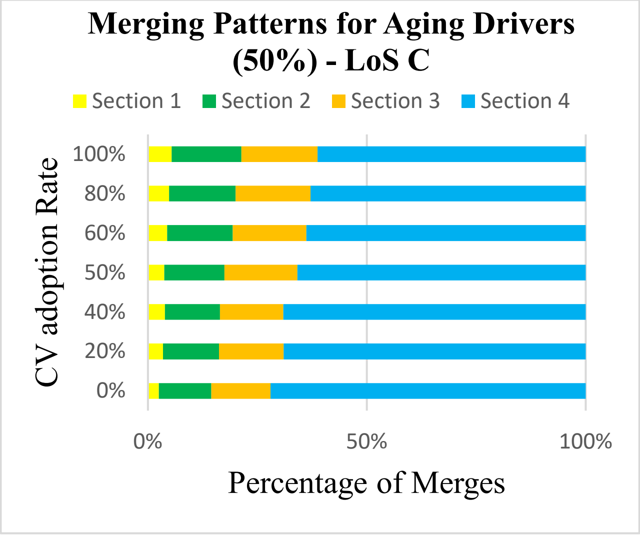



Merging Patterns for Aging Drivers (10%) - LoS C

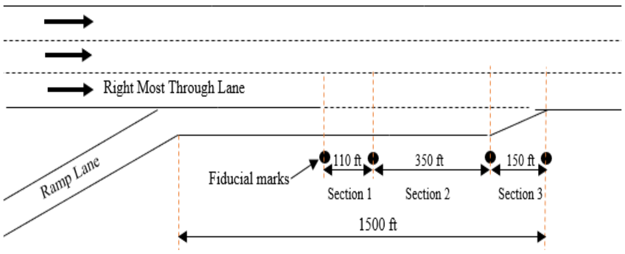

Merging Patterns for Aging Drivers (20%) - LoS C

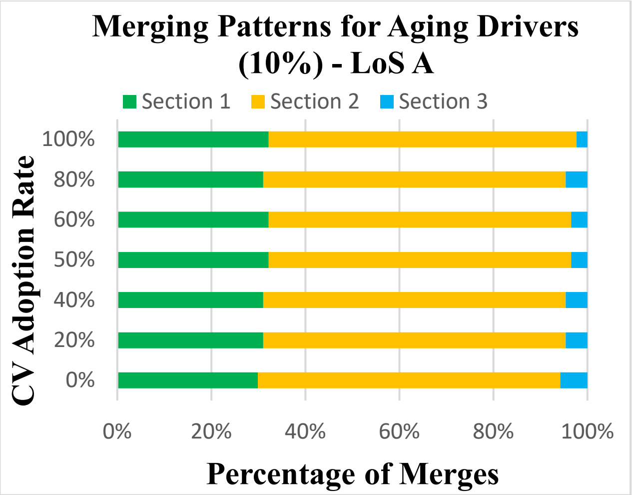

Merging Patterns for Aging Drivers (30%) - LoS C

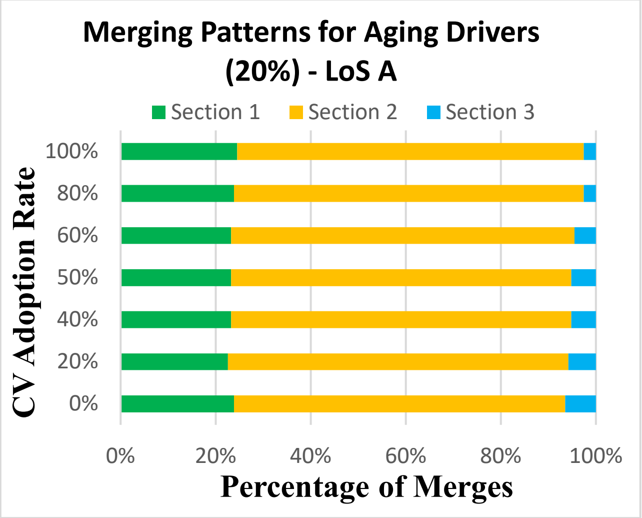

Merging Patterns for Aging Drivers (40%) - LoS C

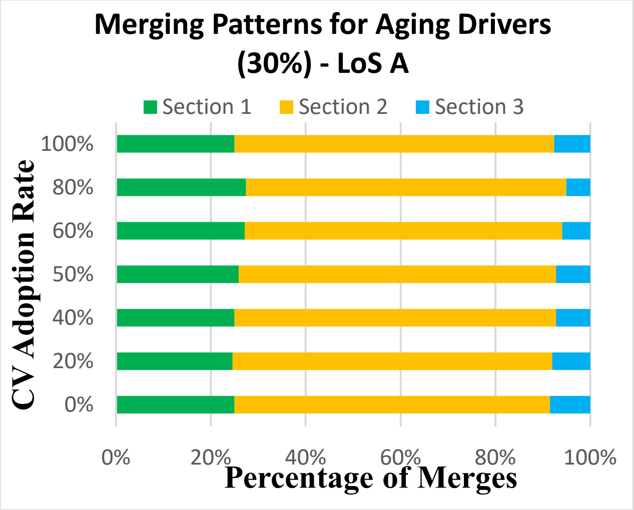

Merging Patterns for Aging Drivers (50%) - LoS C

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




Merging Patterns for Aging Drivers (10%) - LoS A


Merging Patterns for Aging Drivers (20%) - LoS A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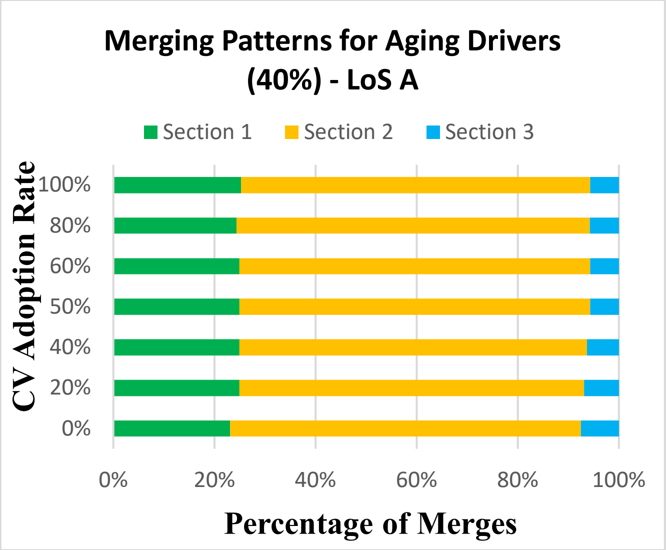
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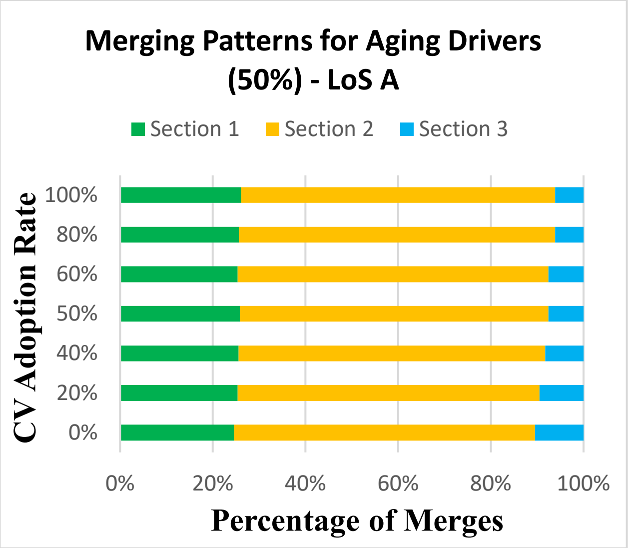
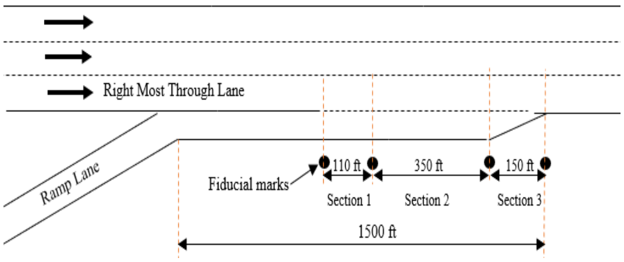
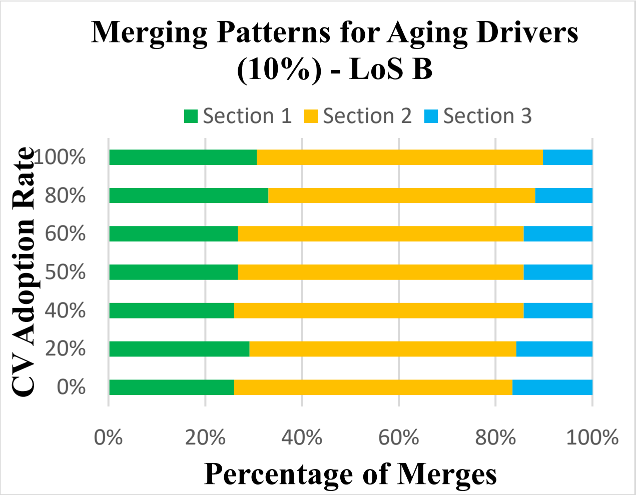
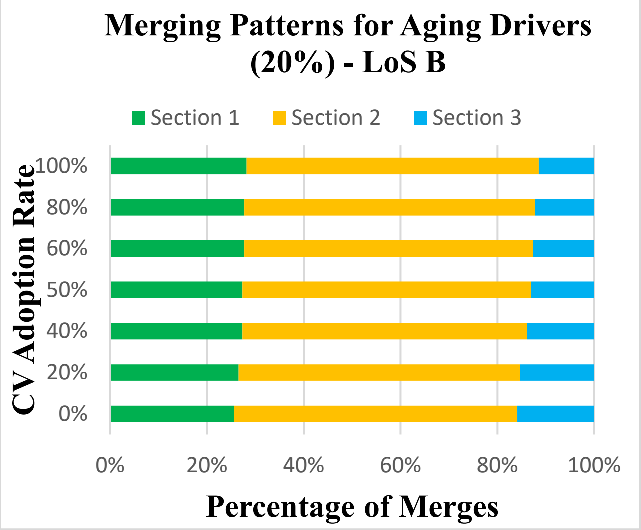
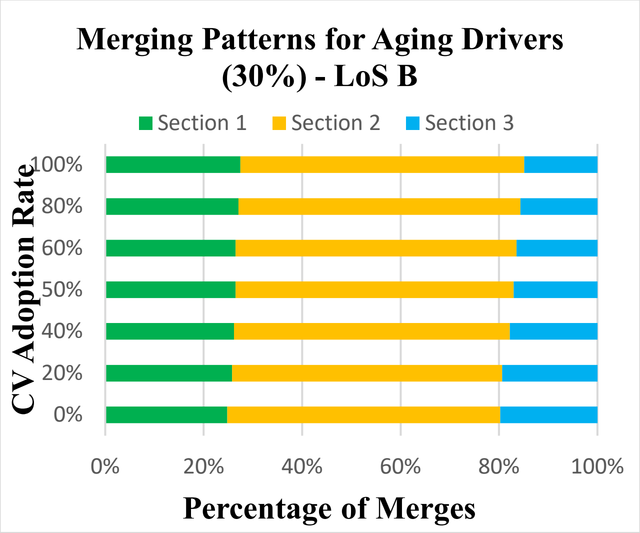

Merging Patterns for Aging Drivers (50%) - LoS A

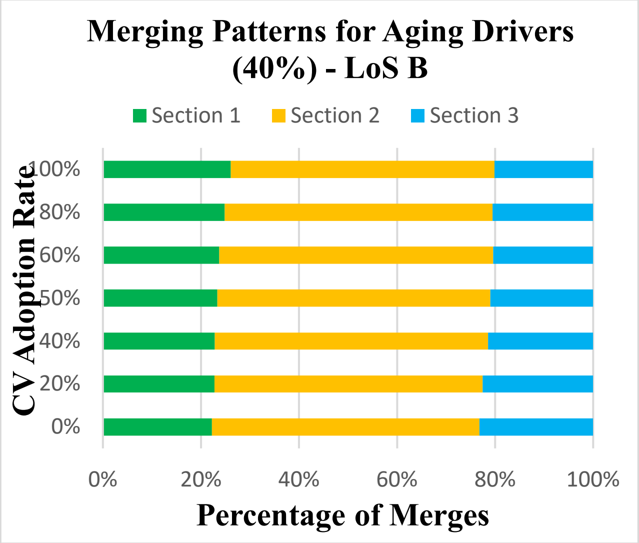
Appendix 5 – Merging patterns at Pine Ridge entrance for various aging drivers' composition on-ramp for **LoS B**

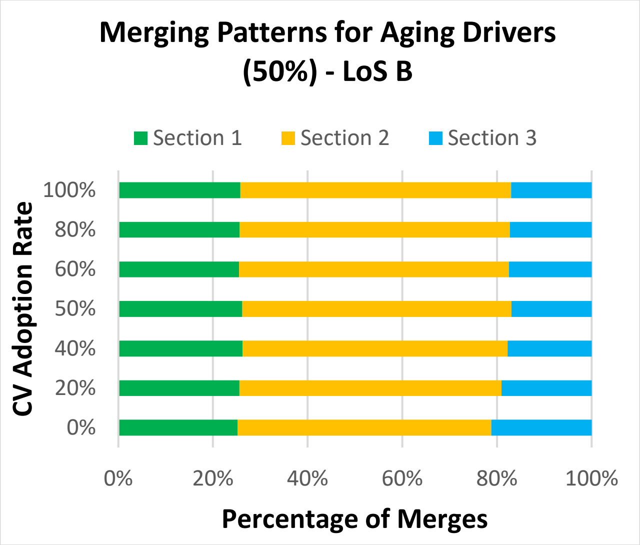




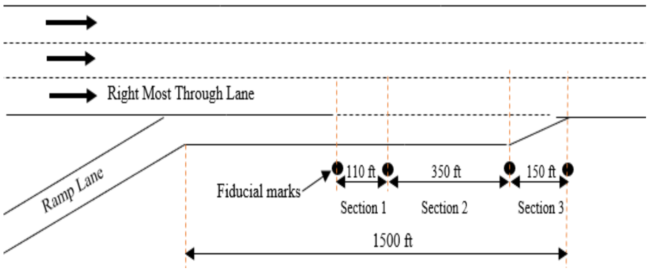


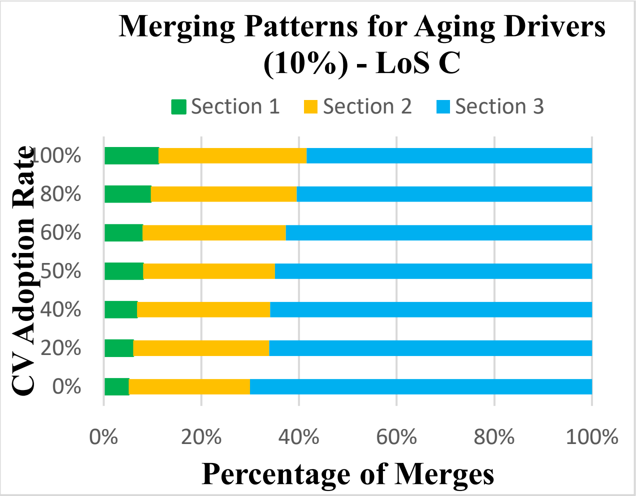


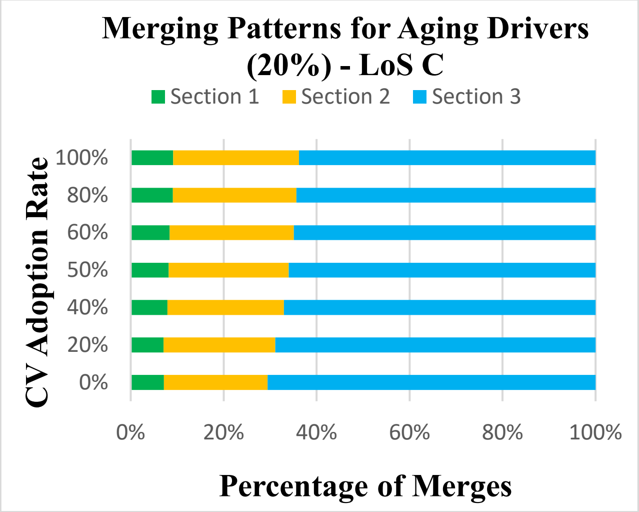


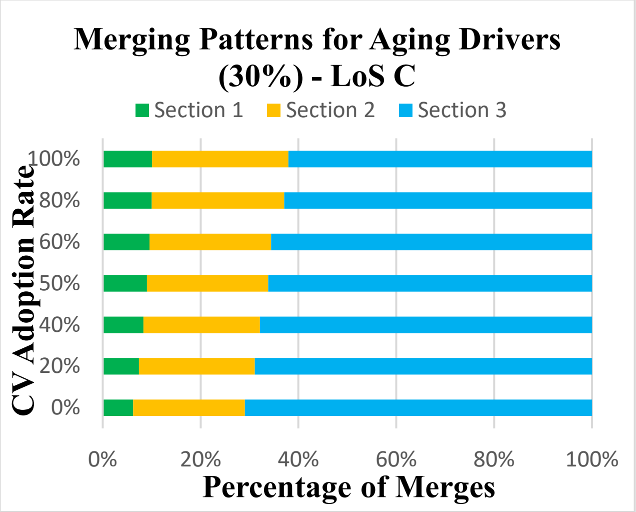


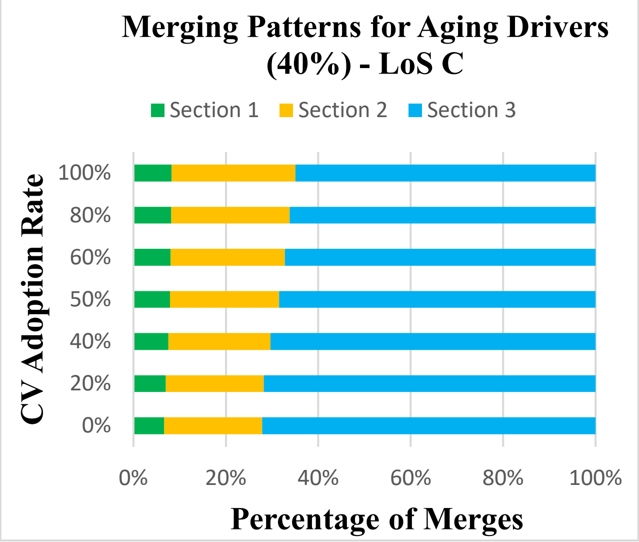
Appendix 6 – Merging patterns at Pine Ridge entrance for various aging drivers' composition on-ramp for **LoS C**

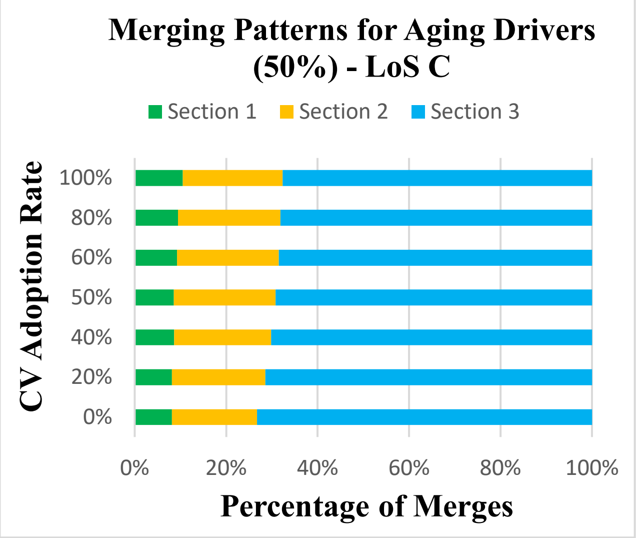




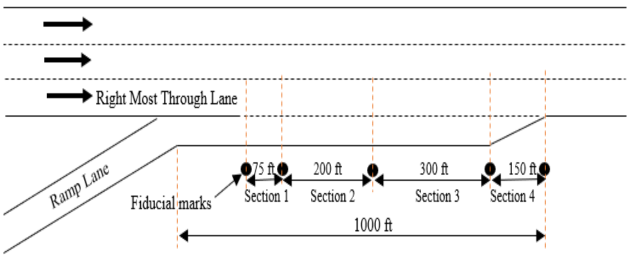


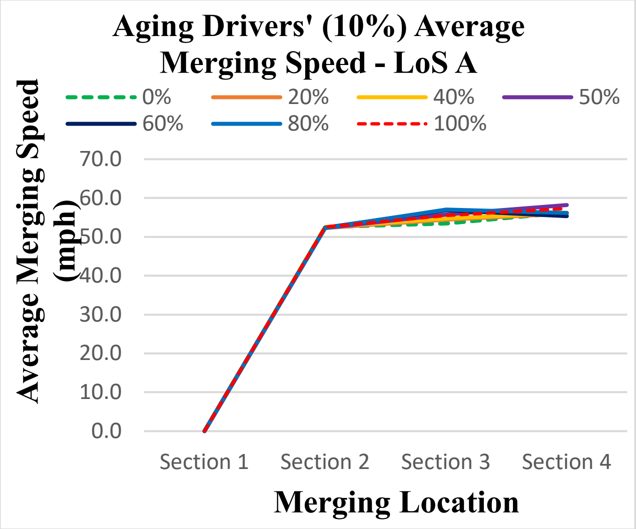


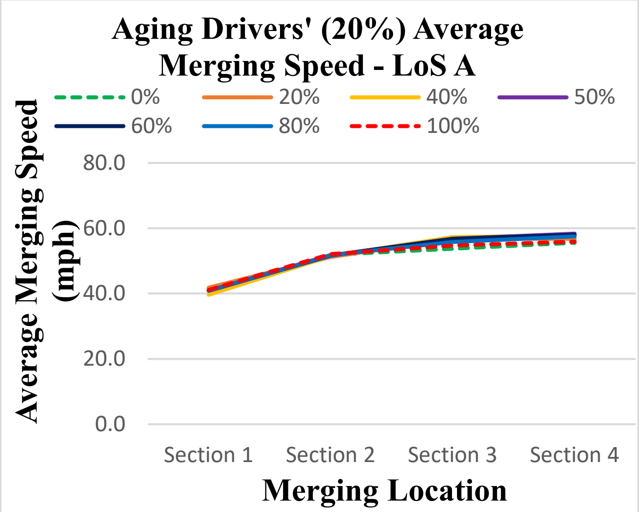


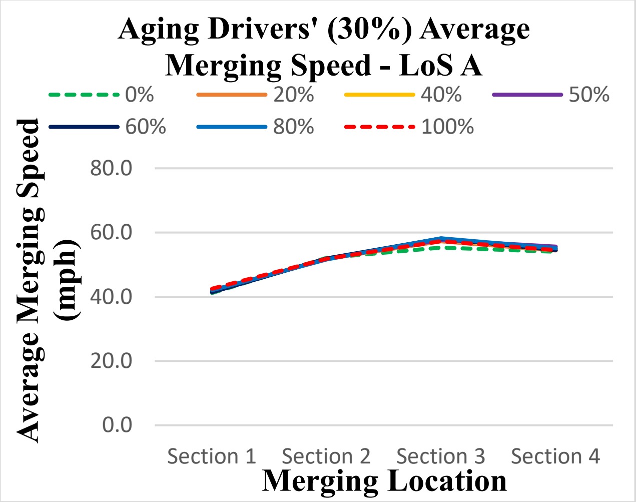


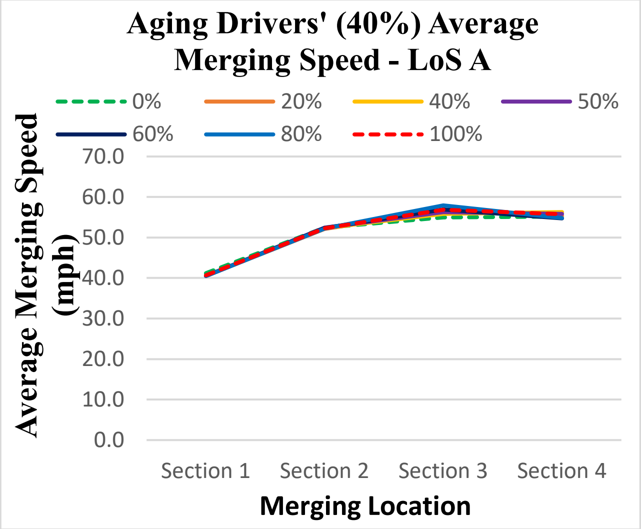
Appendix 7 - Average speed of older drivers during merging at Corkscrew entrance for various composition of aging drivers on-ramp for **LoS A**

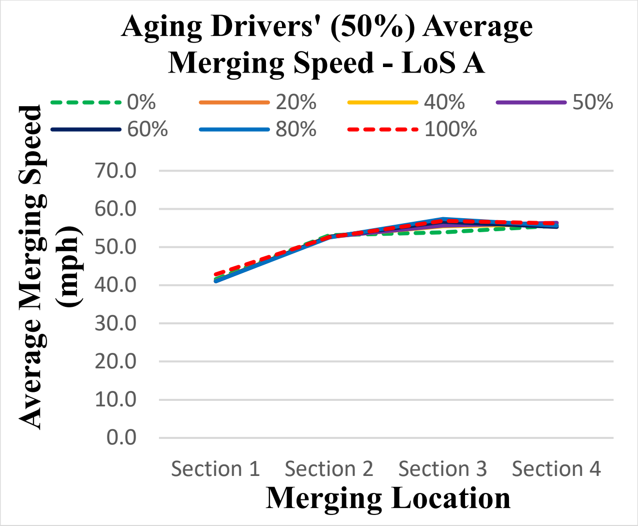




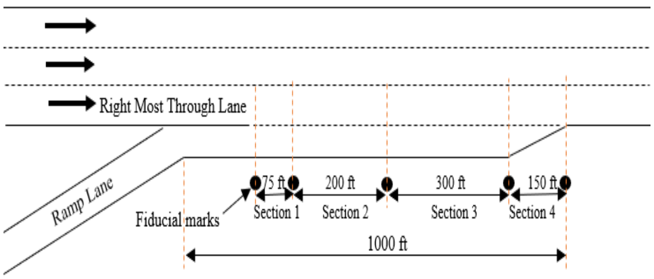


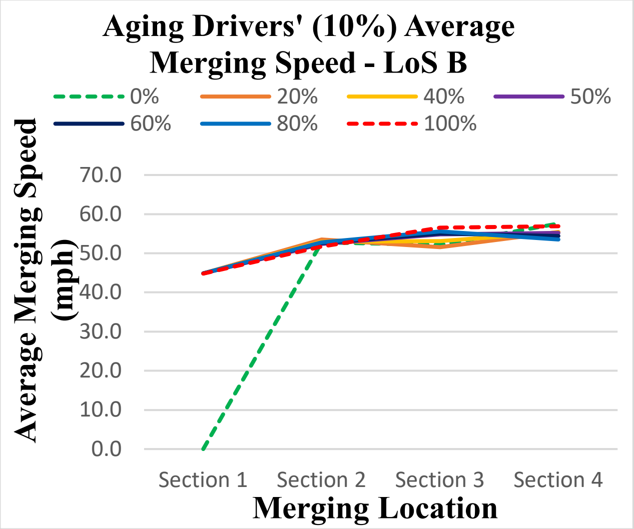


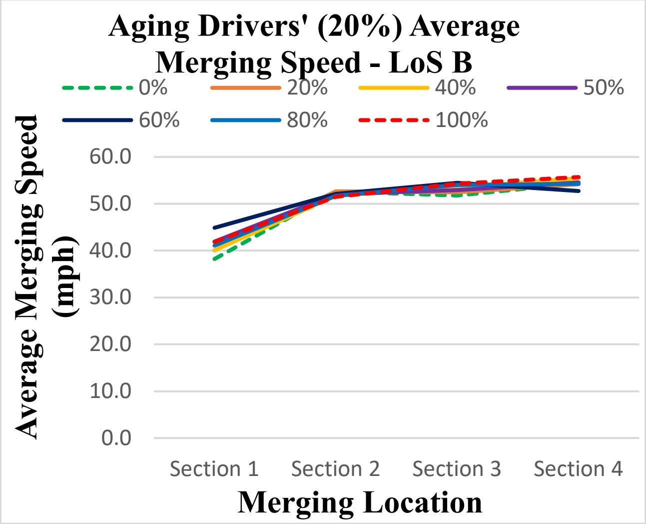


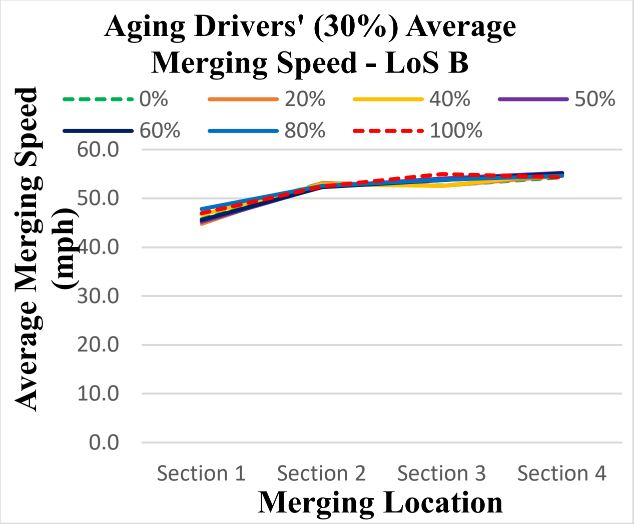


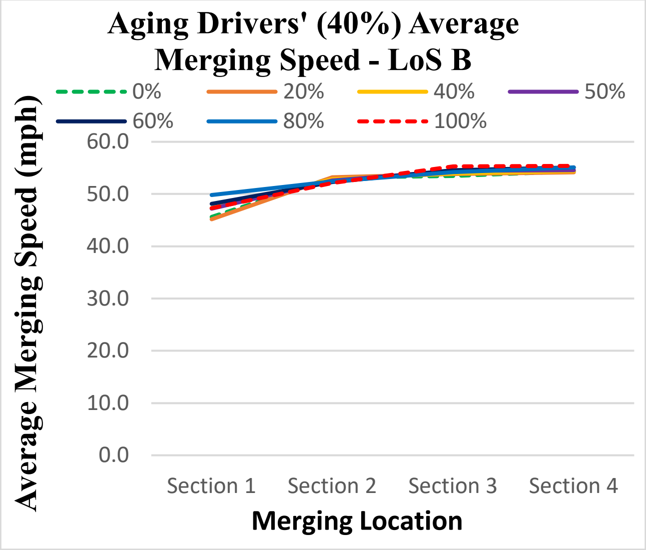
Appendix 8 - Average speed of older drivers during merging at Corkscrew entrance for various composition of aging drivers on-ramp for **LoS B**

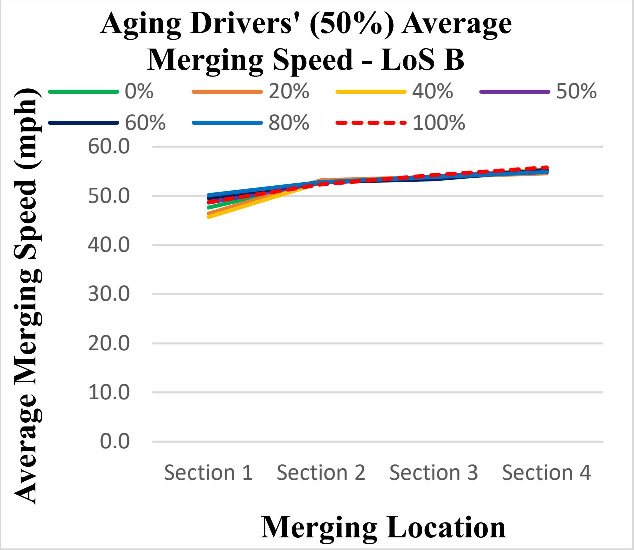



Aging Drivers' (10%) Average Merging Speed - LoS B

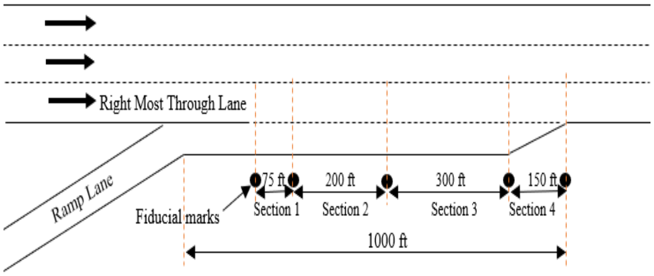

Aging Drivers' (20%) Average Merging Speed - LoS B

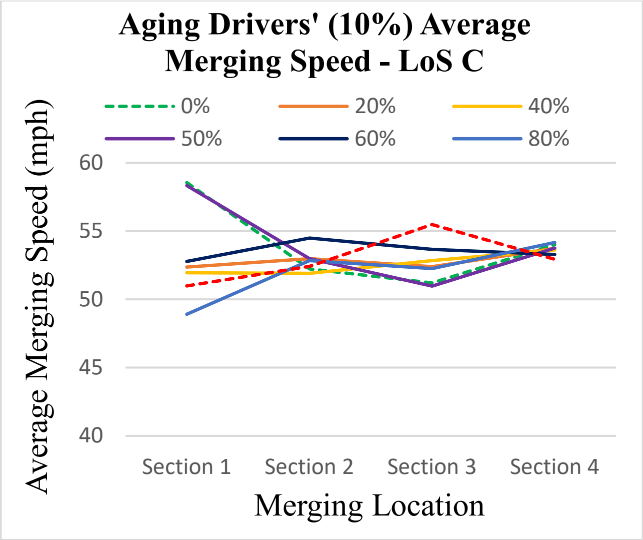

Aging Drivers' (30%) Average Merging Speed - LoS B

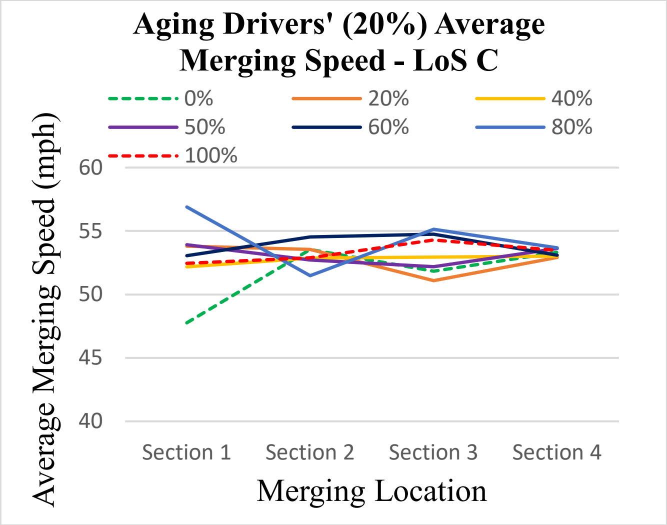

Aging Drivers' (40%) Average Merging Speed - LoS B

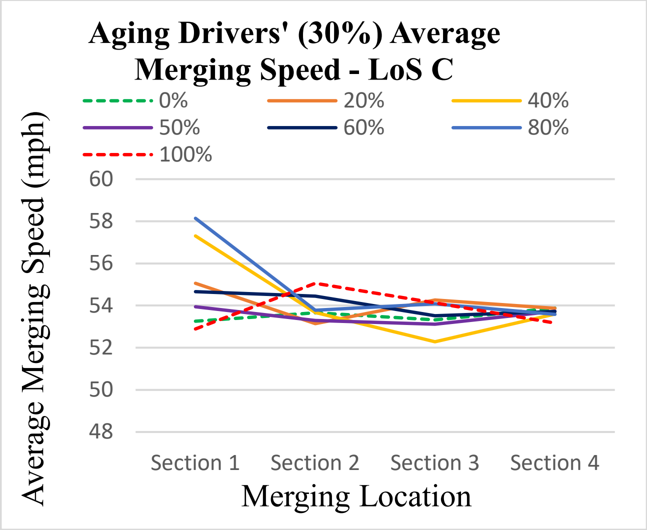

Aging Drivers' (50%) Average Merging Speed - LoS B

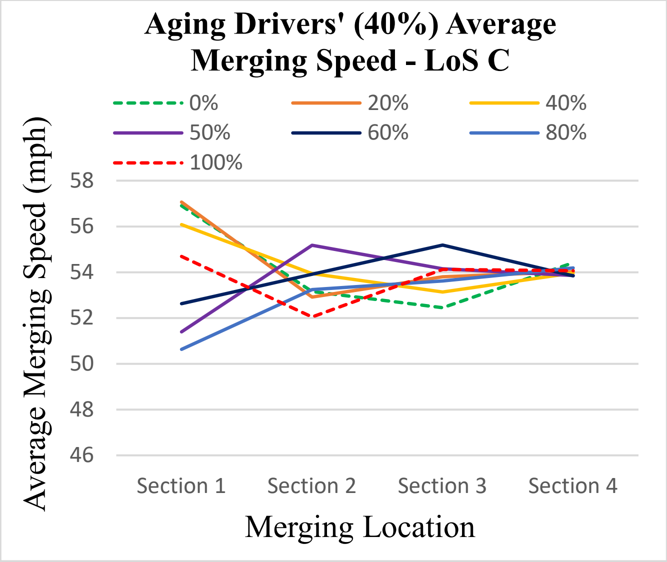
Appendix 9 - Average speed of older drivers during merging at Corkscrew entrance for various composition of aging drivers on-ramp for **LoS C**

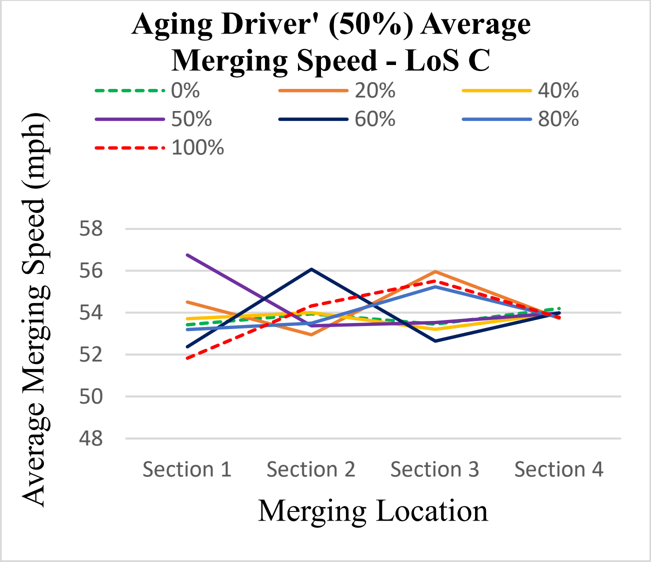



Aging Drivers' (10%) Average Merging Speed - LoS C

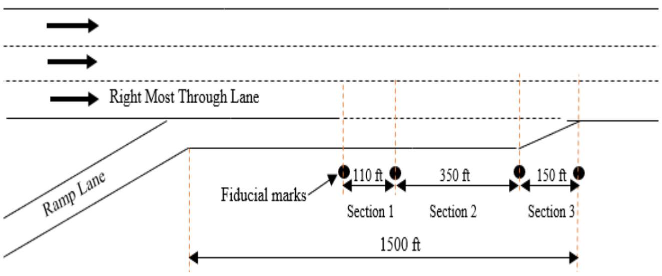

Aging Drivers' (20%) Average Merging Speed - LoS C

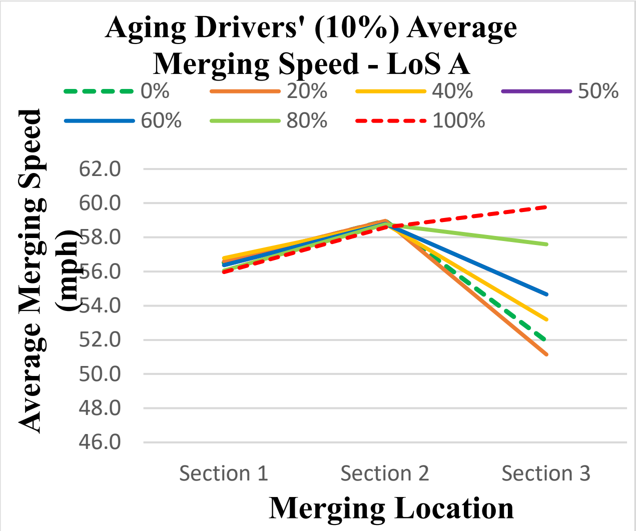

Aging Drivers' (30%) Average Merging Speed - LoS C

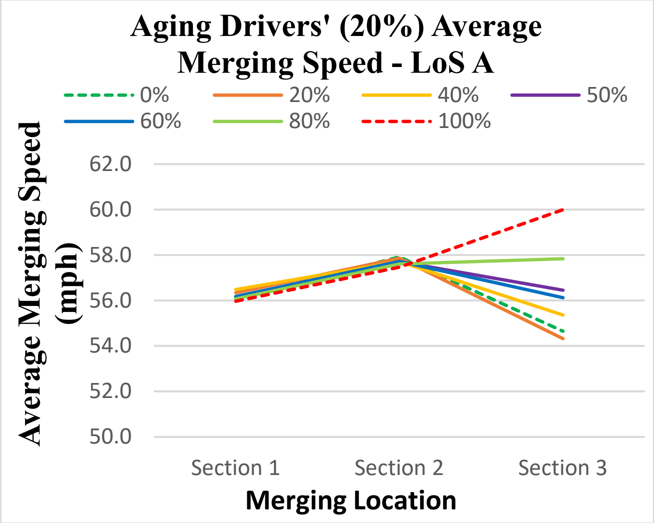

Aging Drivers' (40%) Average Merging Speed - LoS C

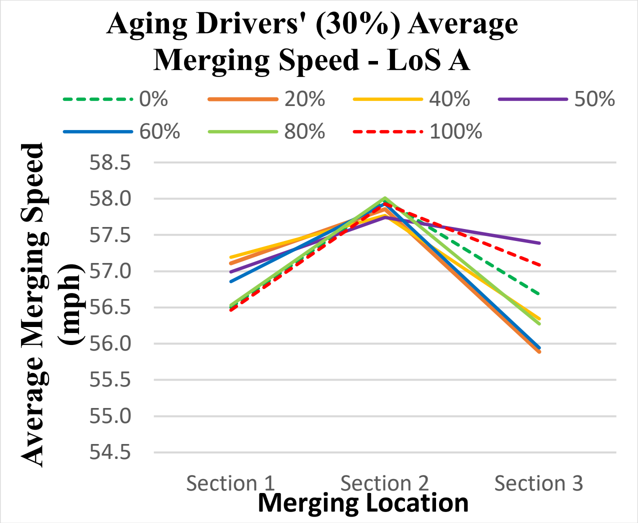

Aging Driver' (50%) Average Merging Speed - LoS C

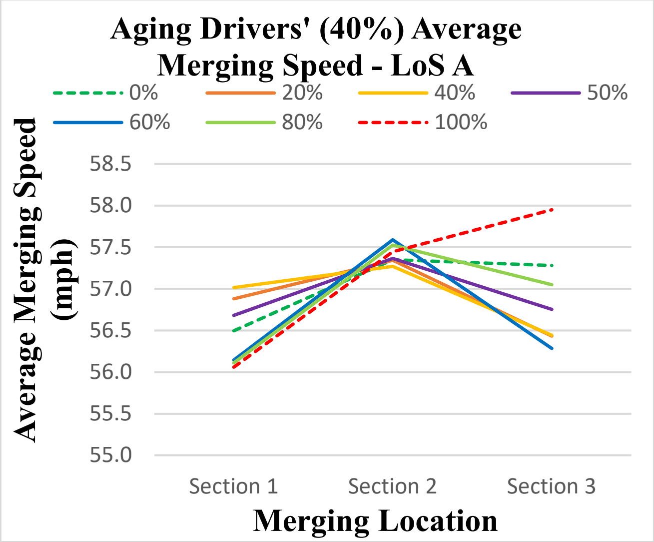
Appendix 10 - Average speed of older drivers during merging at Pine Ridge entrance for various composition of aging drivers on-ramp for **LoS A**

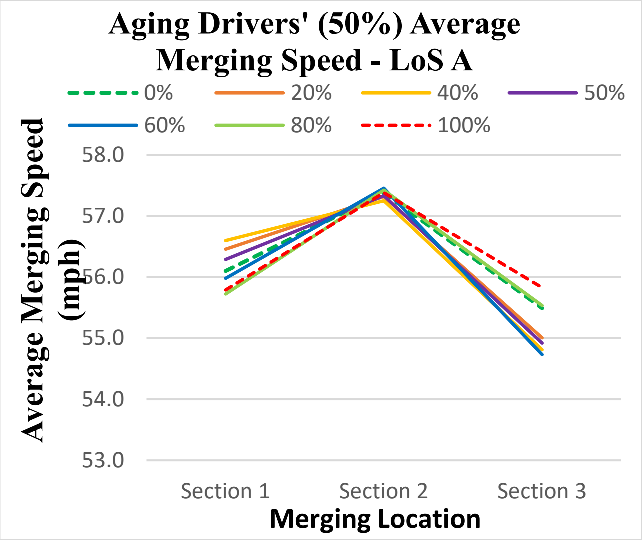



Aging Drivers' (10%) Average Merging Speed - LoS A

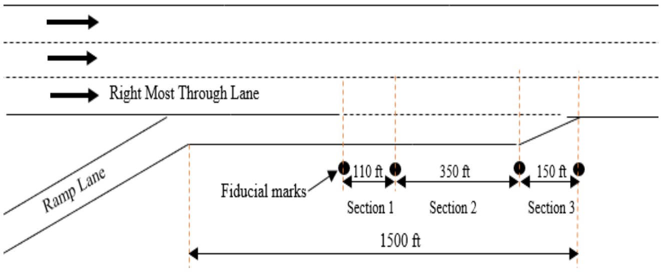

Aging Drivers' (20%) Average Merging Speed - LoS A

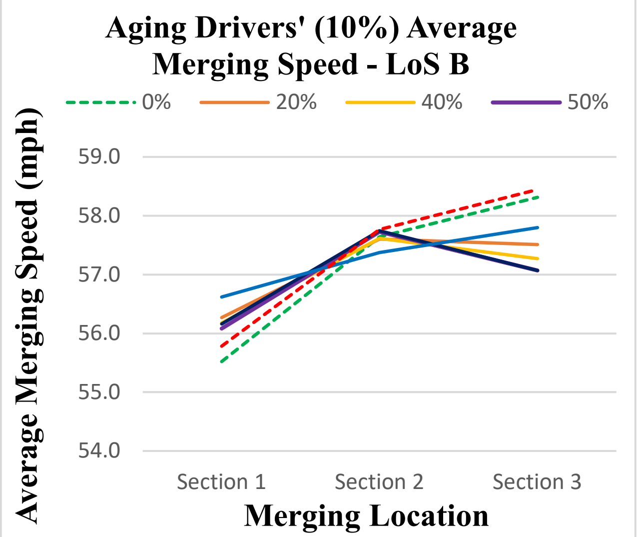

Aging Drivers' (30%) Average Merging Speed - LoS A

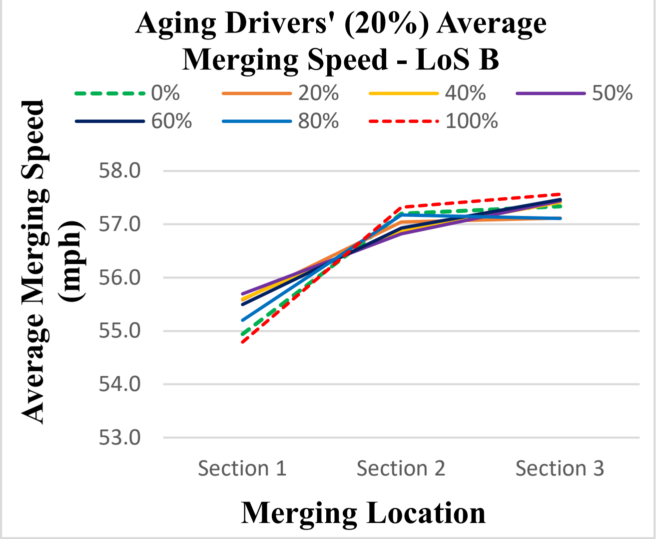

Aging Drivers' (40%) Average Merging Speed - LoS A

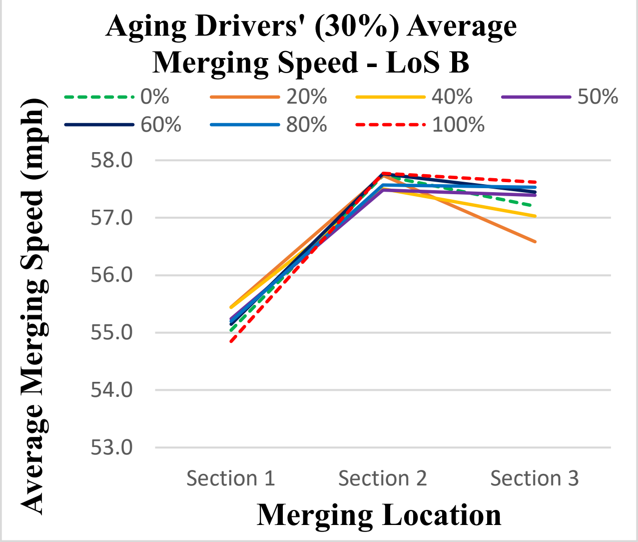

Aging Drivers' (50%) Average Merging Speed - LoS A

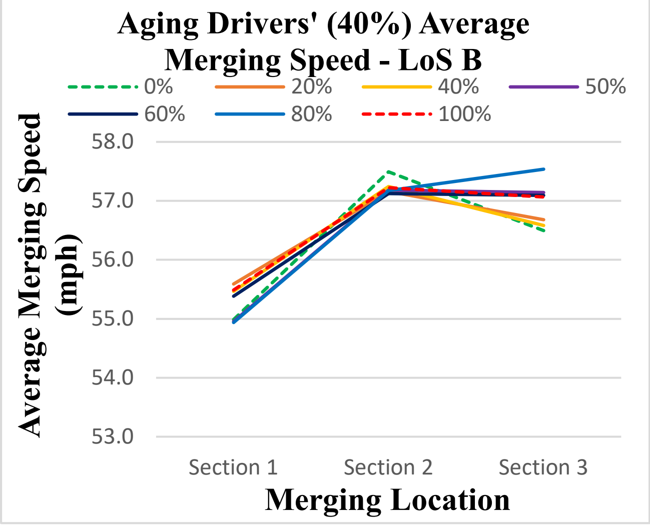
Appendix 11 - Average speed of older drivers during merging at Pine Ridge entrance for various composition of aging drivers on-ramp for **LoS B**

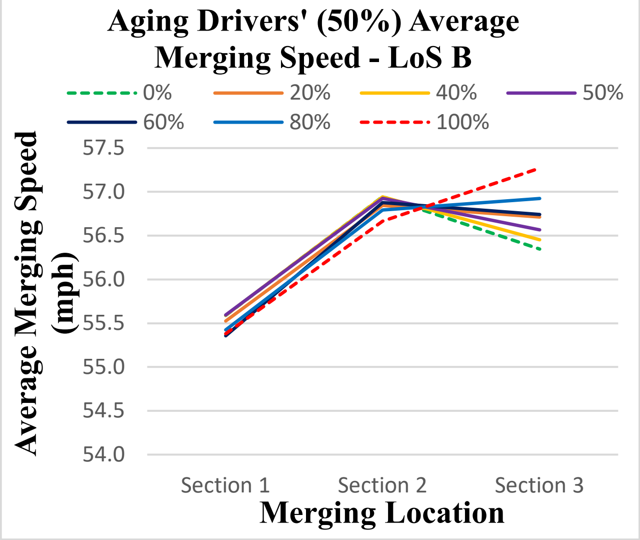




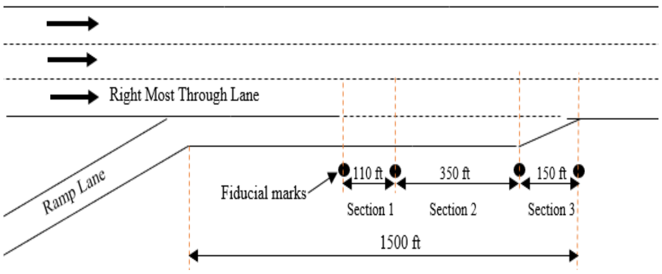


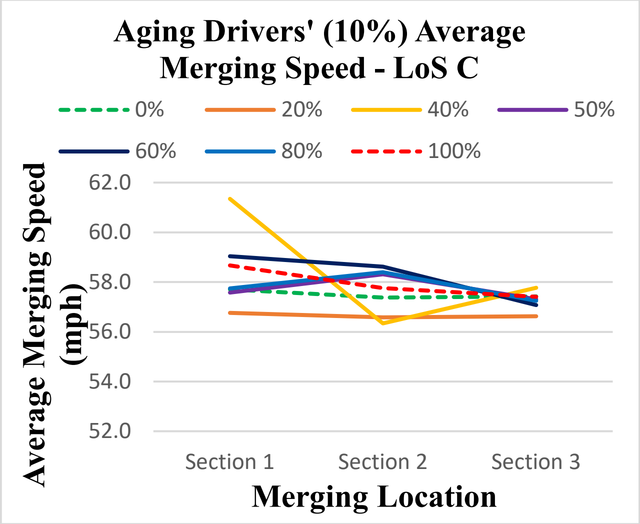


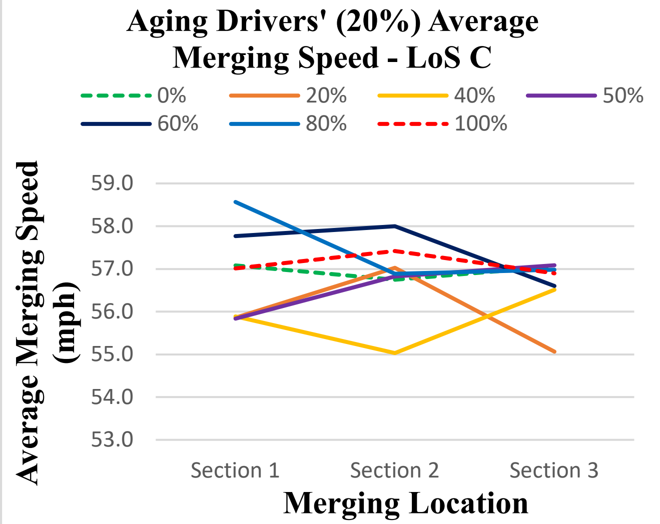


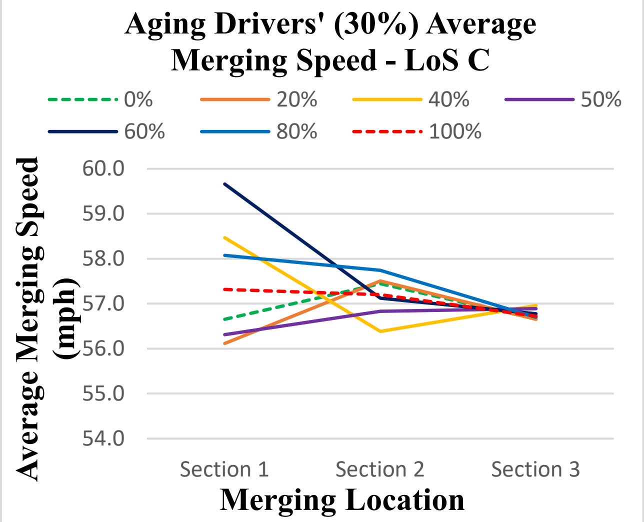


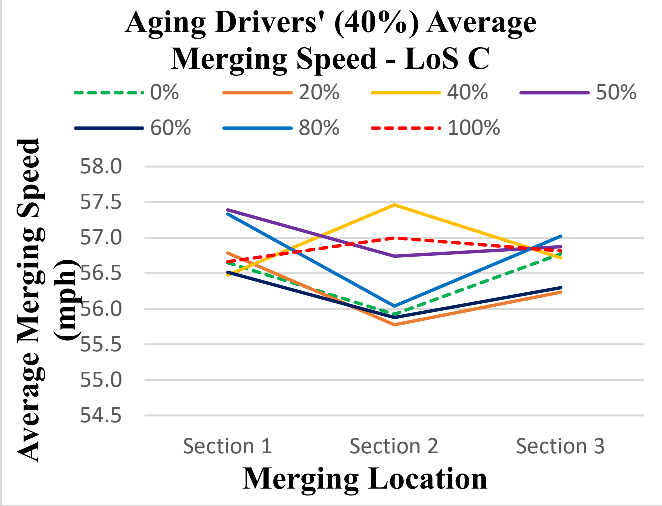
Appendix 12 - Average speed of older drivers during merging at Pine Ridge entrance for various composition of aging drivers on-ramp for **LoS C**

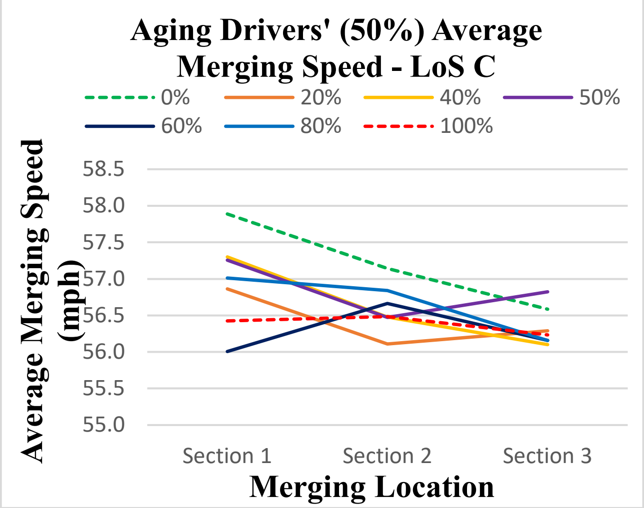



Aging Drivers' (10%) Average Merging Speed - LoS C


Aging Drivers' (20%) Average Merging Speed - LoS C


Aging Drivers' (30%) Average Merging Speed - LoS C


Aging Drivers' (40%) Average Merging Speed - LoS C


Aging Drivers' (50%) Average Merging Speed - LoS C

REFERENCES

AASHTO. (2011). © 2010 by the American Association of State Highway and Transportation Officials. All rights reserved. Duplication is a violation of applicable law. In *Transportation*.

Agerholm, N., & Lahrmann, H. S. (2012). *Identification of Hazardous Road Locations on the basis of Floating Car Data Brief intro to Hazardous Road Locations The Method briefly Floating Car Data Scientific background First results*. (1), 1–12.

American Geriatrics Society & A. Pomidor. (2016). *Clinician ' s Guide to Assessing and Counseling Older Drivers, 3rd Edition*. Washington D.C.

Astarita, V., Festa, D. C., Giofrè, V. P., & Guido, G. (2019). Surrogate Safety Measures from Traffic Simulation Models a Comparison of different Models for Intersection Safety Evaluation. *Transportation Research Procedia*, *37*(September 2018), 219–226. https://doi.org/10.1016/j.trpro.2018.12.186

BEBR. (2017). *Florida Estimates of Population 2017*. Gainesville.

Brewer, M. A., Murillo, D., & Pate, A. (2014). *Handbook for Designing Roadways for the Aging Population*. 428 p.

Bruff, J. T., & Evans, J. (1999). *Elderly Mobility and Safety — The Michigan Approach Final Plan of Action*. (August).

Cantisani, G., Serrone, G. Del, & Biagio, G. Di. (2018). Calibration and validation of and results from a micro-simulation model to explore drivers' actual use of acceleration lanes. *Simulation Modelling Practice and Theory*, *89*(May), 82–99. https://doi.org/10.1016/j.simpat.2018.09.007

Chevalier, A., Coxon, K., John, A., Wall, J., Brown, J., Clarke, E., … Keay, L. (2016). *Exploration of older drivers ' speeding behaviour*. *42*, 532–543. https://doi.org/10.1016/j.trf.2016.01.012

FHWA. (2008). Surrogate Safety Assessment Model and Validation: Final Report. In *Publication No. FHWA-HRT-08-051*.

Florida Department of Transportation. (2014). *Traffic Analysis Handbook: A Reference for Planning and Operations*. (March), 118. Retrieved from http://www.fdot.gov/planning/systems/programs/SM/intjus/pdfs/Traffic Analysis Handbook_March 2014.pdf

Hamed, K. H., & Rao, R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology*, (204), 182–196. https://doi.org/10.1200/jco.2018.36.15_suppl.522

Hidas, P. (2002). Modelling lane changing and merging in microscopic traffic simulation. *Transportation Research Part C: Emerging Technologies*, *10*(5–6), 351–371. https://doi.org/10.1016/S0968-090X(02)00026-8

Hulse, L. M., Xie, H., & Galea, E. R. (2018). Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. *Safety Science*, *102*(August 2017), 1–13. https://doi.org/10.1016/j.ssci.2017.10.001

Immers, B., Martens, M., & Moerdijk, S. (2015). *Tuning highways for future use : the role of the elderly driver*. *31*(0).

Jadaan, K., Zeater, S., & Abukhalil, Y. (2017). Connected Vehicles: An Innovative Transport

Technology. *Procedia Engineering*, *187*, 641–648. https://doi.org/10.1016/j.proeng.2017.04.425

Kenney, J. B. (2011). Dedicated short-range communications (DSRC) standards in the United States. *Proceedings of the IEEE*, *99*(7), 1162–1182. https://doi.org/10.1109/JPROC.2011.2132790

Kockelman, K. M., & Kweon, Y. J. (2002). Driver injury severity: An application of ordered probit models. *Accident Analysis and Prevention*, *34*(3), 313–321. https://doi.org/10.1016/S0001-4575(01)00028-8

Kondyli, A., & Elefteriadou, L. (2009). Driver Behavior at Freeway-Ramp Merging Areas. *Transportation Research Record: Journal of the Transportation Research Board*, *2124*(December), 157–166. https://doi.org/10.3141/2124-15

Laosee, O., Rattanapan, C., & Somrongthong, R. (2018). Physical and cognitive functions affecting road traffic injuries among senior drivers. *Archives of Gerontology and Geriatrics*, *78*(April), 160–164. https://doi.org/10.1016/j.archger.2018.06.015

Lee, C., Hellinga, B., & Ozbay, K. (2006). Quantifying effects of ramp metering on freeway safety. *Accident Analysis and Prevention*, *38*(2), 279–288. https://doi.org/10.1016/j.aap.2005.09.011

Lu, N., Cheng, N., Zhang, N., Shen, X., & Mark, J. W. (2014). Connected vehicles: Solutions and challenges. *IEEE Internet of Things Journal*, *1*(4), 289–299. https://doi.org/10.1109/JIOT.2014.2327587

Lwambagaza, L. (2016). Modeling Older Driver Behavior on Freeway Merging Ramps (University of North Florida). Retrieved from https://digitalcommons.unf.edu/etd/646

Mergia, W. Y., Eustace, D., Chimba, D., & Qumsiyeh, M. (2013). Exploring factors contributing to injury severity at freeway merging and diverging locations in Ohio. *Accident Analysis and Prevention*, *55*, 202–210. https://doi.org/10.1016/j.aap.2013.03.008

Milanes, V., Godoy, J., Villagra, J., & Perez, J. (2011). Automated on-ramp merging system for congested traffic situations. *IEEE Transactions on Intelligent Transportation Systems*, *12*(2), 500–508. https://doi.org/10.1109/TITS.2010.2096812

Mjogolo, F., Njobelo, G., Lwambagaza, L., & Sando, T. (2018). *Impact of Connected Vehicle Technology on Driver's Merging Behavior at Freeway On-ramps Based on Driver's Age: A Micro Simulation Approach*.

NHTSA. (2015). *Traffic Safety Facts 2013 Data Key Findings*. *2015*(February), 2004–2012. https://doi.org/￼DOT HS 812 148

Ortman, B. J. M., Velkoff, V. a., & Hogan, H. (2014). An aging nation: The older population in the United States. *US Department of Commerce: US Census Bureau*, *1964*, 1–28. https://doi.org/10.1590/S1519-69842001000300008

PTV. (2018). *PTV VISSIM 11 User Manual*.

Radu Popescu-Zeletin, & Rigani, M. A. (2010). *Vehicular-2-X Communication State-of-the-Art and Research in Mobile Vehicular Ad hoc Networks*. Berlin: Springer.

Roberts, A. W., Ogunwole, S. U., Blakeslee, L., & Rabe, M. A. (2018). *The Population 65 Years and Older in the United States: 2016*. Washington, DC.

Safety Mobility for Life Coalition. (2018). *Florida ' s Guide for Aging Drivers*. Florida.

Sarvi, M., Kuwahara, M., & Ceder, A. (2004). A Study on Freeway Ramp Merging Phenomena in Congested Traffic Situation by Traffic Simulation Combines with Driving Simulator. *Computer-Aided Civil and Infrastructure Engineering*, *19*, 351–363. https://doi.org/10.1111/j.1467-8667.2004.00362.x

Scarinci, R., Hegyi, A., & Heydecker, B. (2017). Definition of a merging assistant strategy using intelligent vehicles. *Transportation Research Part C: Emerging Technologies*, *82*, 161–179. https://doi.org/10.1016/j.trc.2017.06.017

Scarinci, R., & Heydecker, B. (2014). Control Concepts for Facilitating Motorway On-ramp Merging Using Intelligent Vehicles. *Transport Reviews*, *34*(6), 775–797. https://doi.org/10.1080/01441647.2014.983210

Scarinci, R., Heydecker, B., & Hegyi, A. (2015). Analysis of Traffic Performance of a Merging Assistant Strategy Using Cooperative Vehicles. *IEEE Transactions on Intelligent Transportation Systems*, *16*(4), 2094–2103. https://doi.org/10.1109/TITS.2015.2394772

Stipancic, J., Miranda-Moreno, L., & Saunier, N. (2018). Vehicle manoeuvers as surrogate safety measures: Extracting data from the gps-enabled smartphones of regular drivers. *Accident Analysis and Prevention*, *115*(March), 160–169. https://doi.org/10.1016/j.aap.2018.03.005

Stipancic, J., Miranda-moreno, L., Saunier, N., & Labbe, A. (2019). Network screening for large urban road networks : Using GPS data and surrogate measures to model crash frequency and severity. *Accident Analysis and Prevention*, *125*(February), 290–301. https://doi.org/10.1016/j.aap.2019.02.016

Strauss, J., Zangenehpour, S., Miranda-Moreno, L. F., & Saunier, N. (2017). Cyclist deceleration rate as surrogate safety measure in Montreal using smartphone GPS data. *Accident Analysis and Prevention*, *99*, 287–296. https://doi.org/10.1016/j.aap.2016.11.019

Talebpour, A., & Mahmassani, H. (2015). Influence of Autonomous and Connected Vehicles on Stability of Traffic Flow. *Transportation Research Board 94th Annual Meeting*, 1–16. https://doi.org/No. 15-5971

Tampere, C. M. ., Hogema, J. H., Katwijk, R. T. van, & Van Hem, B. (1999). Exploration of the impact of Intelligent Speed Adaptation and co-operative following and merging on highu,ays using MIXIC. In *TNO report INRO; 99lnW162*. https://doi.org/10.1109/IVS.2003.1212954

Transportation Research Board. (2000). Highway capacity manual. In *Environmental Protection*. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000746.

Transportation Research Board. (2016). Vol. 2: Uninterrpted flow, Chap.12: Basic freeway and multilane highway segments. In *Highway capacity manual 6th EDITION* (pp. 205–248). https://doi.org/10.1007/978-3-319-05786-6_7

Ulak, M. B., Ozguven, E. E., Moses, R., Abdelrazig, Y., & Sando, T. (2018). *Assessment of Traffic Performance Measures and Safety based on Driver Age and Experience : A Microsimulation Based Analysis for an Unsignalized T- Intersection*. (May).

Wang, C., & Stamatiadis, N. (2014). Evaluation of a simulation-based surrogate safety metric. *Accident Analysis and Prevention*, *71*, 82–92. https://doi.org/10.1016/j.aap.2014.05.004

Xie, K., Yang, D., Ozbay, K., & Yang, H. (2019). Use of real-world connected vehicle data in identifying high-risk locations based on a new surrogate safety measure. *Accident Analysis and*

Prevention, *125*(February 2018), 311–319. https://doi.org/10.1016/j.aap.2018.07.002

Zhao, P., & Lee, C. (2018). Assessing rear-end collision risk of cars and heavy vehicles on freeways using a surrogate safety measure. *Accident Analysis and Prevention*, *113*(January), 149–158. https://doi.org/10.1016/j.aap.2018.01.033