

IMPACT OF LEVEL 3 AUTOMATED VEHICLE
MERGING ON 2-TO-1 LANE FREEWAY

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EXECUTIVE SUMMARY

The better of automated system is continuously developed for vehicles. It is becoming to the new generation of vehicle that could drive by itself without human driver. Recently, the level 3 automated vehicle is being developed by many manufactures and it is soon expected to be applicable on roadway. The level 3 automated vehicle is firstly expected to travel on roadway concurrently with the manual vehicle and could be fully used in the future.

Two-lane highways play an important role of mobility in the state and county highway systems. The maintenance or reconstruction of roadway are required because of the limited life cycle of the pavement. The capacity could significantly drop due to the lane closer from the work zone. Many strategies are used to control the traffic to efficiently and safely pass through the work zone.

The static early merge, late merge and hybrid are used in this study. Early merge allows vehicle to change lane to the open lane before reaching the merge point where the closed lane before the merge point is not being used by vehicle. Late merge allows vehicle to stay on its lane until the merge point and perform alternative merge or zipper merge pattern. Hybrid strategy is the combination of early merge and late merge strategies which allows vehicle to merge whenever it finds acceptable gap to change lane to open lane. Vehicle could continue moving to the merge point when the gap is not sufficient and perform the alternative merge pattern.

This study aims to investigate the impact of level 3 automated vehicle passing through the work zone on 2-to-1 lane drop freeway. The different traffic flow and market penetration of level 3 automated vehicle varies in each simulation. Three merging strategies is simulated to find the best practice between early merge, late merge and hybrid strategies.

The simulation model is created by using VISSIM microsimulation tool. The total of 90 simulations with three merging strategies at different traffic flow and market penetration are performed. The traffic flow varies from 1,000 vphpl to 2,000 vphpl with incremental of 200 vphpl. The market penetration varies from 40% to 100% with incremental of 20% and the other 0% is also applied.

Two performance of vehicle throughput and travel time are investigated in the simulation. After running all the simulations and analyzing the results, it could be found that the level 3 automated vehicle helps improve the mobility performance. The higher market penetration of level 3 automated vehicle causes the higher vehicle throughput and less travel time. It has significant impact on early merge and hybrid strategies but only slightly impact to late merge strategy. From three merging strategies, the hybrid strategy is the best practice for vehicle with mix traffic of level 3 automated vehicle passing through the work zone on 2-to-1 lane drop freeway.

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1. INTRODUCTION

1.1 Problem statement

Many of new vehicles on the market recently are installed with automated system such as sensing technologies that help the driver better monitor the vehicle's environment effectively. The higher autonomous system of automated vehicle is very interesting to the new era of transportation. The level 3 automated vehicle is soon applicable on roadway.

Two-lane highways play an important role of mobility in the state and county highway systems. With the limited pavement life cycle and the overdue road infrastructure rehabilitation, regular maintenance and reconstruction of existing highways are frequent. According to the increasing amount of highway traffic volume, construction and maintenance activities on highways, lane closure is needed in order to conduct the construction or maintenance work. Therefore, the capacity of roadway is reduced during the closure period. It could affect both mobility and safety performances. The rate of vehicle that merge and pass through the work zone area and the travel time decrease because of the bottleneck capacity at lane drop. The increasing delay and decreasing throughput are the major cause resulting in less mobility performance.

The automated vehicle is expected to be operated concurrently with the manual vehicle in the near future. At the work zone area, the capacity drop from lane closure could cause significantly delays, less vehicle throughput and longer travel time. Therefore, the impact of the level 3 automated vehicle merging into the work zone is worth investigated for the best practice on 2-to-1 lane drop freeway.

Highly automated vehicle or HAV could be operated without human driver [1]. The control system of HAV could provide more safety and mobility on roadway. It would be a great benefit in

the future for the capacity and safety on roadway. According to current research, it mostly focuses on level 2 HAV or level 5 HAV and some with the connectivity function. From the industry view, it rather focuses on automated driving capability than vehicle connectivity ability.

Therefore, this thesis focuses on the impact of level 3 automated vehicle on merging into the work zone by 2-to-1 lane drop on freeway. To observe the vehicle throughput and travel time through the work zone could possibly define the better practice for each merging strategy to use and the benefit of operation of level 3 automated vehicle. The investigation is conducted by using VISSIM microsimulation tool which can perform various driving behaviors on each type of vehicles.

1.2 Objectives

The primary objective of this research is to find the best practice of merging strategy on 2-to-1 lane drop of freeway when the level 3 automated vehicle is mixed in the traffic at different market penetration with different traffic flow. The key objectives of this study could be divided as follows:

- Find the best practice of implementing the merging strategy passing through the work zone on 2-to-1 lane drop freeway for the traffic mix with level 3 automated vehicle at different market penetration and at different traffic flow.
- Determine the impact of market penetration of level 3 automated vehicle passing the 2-to-1 lane drop on freeway at each traffic flow in each merging scenario.
- Determine the efficiency of level 3 automated vehicle on merging at 2-to-1 lane drop at different traffic flow in each merging scenario.

1.3 Organization

This research is organized into 5 chapters, references and appendices. First chapter introduces the importance of this research with the hypothesis and objectives. Chapter 2 provides a literature review of relevant aspects to this research which are automated vehicle, work zone and merging strategy. Chapter 3 describes the methodology of this research showing how the simulation network is done by VISSIM microsimulation tool and the scenarios used. Chapter 4 provides the results and a detailed analysis from the simulations. Chapter 5 summarizes the results and concludes some remarks. Moreover, it represents the recommendation for the future works. Lastly, the references and appendices provide the citation and some example results respectively.

2. LITERATURE REVIEW

This chapter provides a better understanding in detail of what relevant to this research. It includes the topic of automated vehicle which level 3 automated vehicle is used for the simulation and also provides the detail about the market penetration for the automated vehicle which is the main factor to simulate the network for this thesis. Moreover, temporary traffic control for work zone on freeway topic is used to build the simulation network for this study. Lastly, the merging strategies include static and dynamic for early merge and late merge. According to the simulation network for this thesis, static early merge and static late merge is used.

2.1 Automated vehicle

Automated vehicle has initiated in early 1920s [2]. It was known as a vehicle that driven by itself using radio and magnets as a guide [3]. Presently, automated vehicle is much different than before, it could receive input data from the physical sensors such as radar, LIDAR, ultrasonic, and cameras [4]. Those sensors could assist and replace human driver to perform driving task and monitoring the driving environment.

Society of Automotive Engineers (SAE) and National Highway Traffic Safety Administration (NHTSA) have both defined the classification of automated vehicle as a level. NHSTA has adopt the standard of SAE in October 2016 [5]. Therefore, the classification of automated vehicle in this thesis is referred from SAE.

According to the Society of Automotive Engineers (SAE), it has defined six levels of automation which range from level 0 which is manual driving, up to level 5 which is full automation without driver. From level 0 to level 2, driver must monitor the environment at all

time, while, from level 3 to level 5, automated driving system monitors driving environment. The detail of each automation level is explained and presented in figure 1.

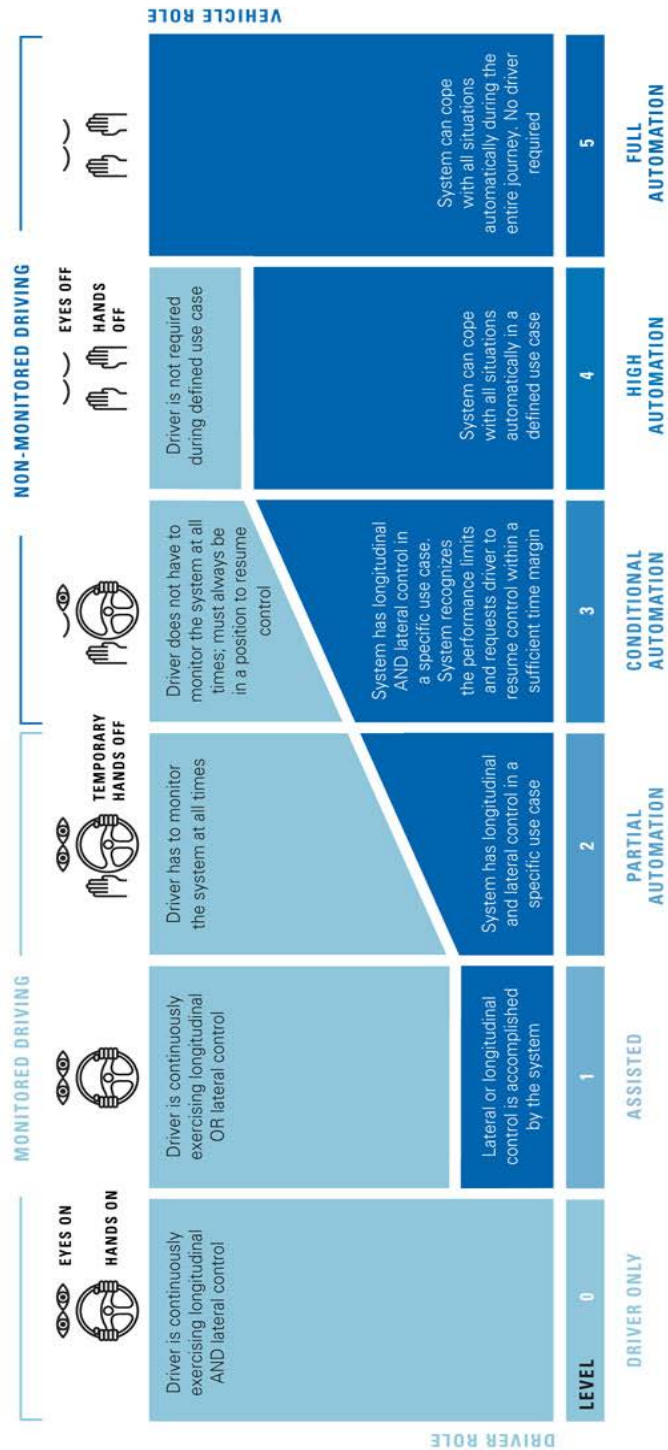


Figure 1: Level of automated vehicle

- Level 0 No Automation

For level 0 automated vehicle, the vehicle does not have any automation and be solely controlled by the driver. Human driver needs to perform the dynamic task full-time, even the human driver has been informed by enhanced warning or intervention system [6]. Human driver is responsible for the primary vehicle controls such as brake, steering, throttle, motive power and the monitoring of driving environment. Most of vehicle at this level is 1990s vehicle.

- Level 1 Driver Assistance

For level 1 automated vehicle, the driver assistance systems are included in vehicle. The driving mode-specific is executed by a driver assistance system which are steering or acceleration/ deceleration. It performs by using information about the driving environment with the expectation that the human driver performs all remaining aspects of the dynamic driving task [6]. Vehicle involves one or more specific control functions such as electronic stability control (ESC) and anti-lock braking system (ABS) which help driver to regain control of vehicle or stop faster than acting alone. Moreover, in the USA, all passenger cars are recently required ESC and ABS to be installed [7].

- Level 2 Partial Automation

For level 2 automated vehicle, the vehicle has automation of at least two primary control functions such as adaptive cruise control (ACC) and Lane Keeping Assist (LKA). The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task [6]. The difference between level 1 and level 2 automation is that level 2 automation can perform both

longitudinal and lateral control of vehicle, while level 1 automation can perform only either one of the control. Moreover, level 2 feature is expected to mandate in all vehicle in the near future [7].

- Level 3 Conditional Automation

For level 3 automated vehicle, the vehicle is able to perform the dynamic task and monitor driving environment at certain conditions, but driver is expected to be available for occasional control at all times. The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene [6]. Level 2 and level 3 automation can perform both longitudinal and lateral control of vehicle. The difference between level 2 and level 3 automation is that human driver of level 3 automation does not need to monitor driving environment at all time as in level 2 automation. Google car is an example of limited self-driving automation.

- Level 4 High Automation

For level 4 automated vehicle, the driver is completely no need to perform any driving task. The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene [6]. The system does not request driver to take over under certain conditions. There is currently no vehicle at this level of automation, but some manufacturers are aiming to deliver in 2020 [8].

- Level 5 Full Automation

For level 5 automated vehicle, the vehicle has full driving automation capability. The vehicle has full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver [6]. Human driver does not have to perform anything during the entire trip, therefore, the driver is not needed. The vehicle at this level is expected to be available in many years due to the reliable and affordable on public road.

2.1.1 Benefits of automated vehicles

Automated vehicles can bring many benefits to our lives, such as, leading to safer roads, less congestion which could benefit human society. The more technology on automated vehicle improve, the better people's living standards increase.

According to the statistics of US Department of Transportation [1], more than 35,000 people died on US roadways and around 94 percent of all crashes caused by human errors in 2015. Therefore, the automated vehicle is expected to mitigate the risks of human errors by using technology which can correct such mistakes. It corrects the mistakes by collecting and calculating the human repeated mistakes in the system. Therefore, the probability of mistakes is decreasing.

Automated vehicle could improve fuel efficiency. It could possibly make fuel economy gain up to 10% and losses of up to 3 percent [9]. The reason for this improvement is because the system of automated vehicle could control and manage brakes, throttle and steering better than human. Moreover, the multiple manufacturers are currently focusing on combining automated vehicle technologies and electric vehicles together to build smart and sustainable road vehicle for

the future. Electric-driven automated vehicles will bring even greater efficiency benefit to the society.

According to the purpose of this research, the benefit of transportation operation is the major focus. Automated vehicle is expected to use the roadway more efficiently from its higher sensing and anticipating to the leading vehicle's braking or accelerating and decelerating than human driver [10]. It can smooth the traffic from rapid acceleration of human driving vehicle with only 10 percent of semi-automated vehicle [11]. It is estimated to improve the highway capacity by up to 40 percent if all vehicles are semi-automated [12]. According to the cooperative adaptive cruise control (CACC) system, it could improve the freeway capacity by as much as 50 to 80 percent when the entire of fleet of traffic is equipped with CACC. Moreover, at 50 percent market penetration, the capacity is increased by 22 percent [13].

2.1.2 Market penetration

The market penetration and adoption rate are crucial to automated vehicle. It relies on various factors such as cost, reliability and law enforcement. The rate of adoption is uncertain regarding to those factors [10]. It is predicted to reach 8 million of automated vehicle within ten years after introducing the full level of automated vehicle and reach the saturation in 35 years after the introducing of 75% market of fully automated vehicle [14]. Moreover, it is expected to have the market share around 15 to 20 percent globally in 2030 [15].

Level 1 autonomous recently has 100% market penetration in 2011 since NHTSA has mandated ABS and ESC installation for vehicle. Level 1 and level 2 automated vehicles are currently used in traffic nowadays. However, the market penetration of level 2 automated vehicle is not easily to specify. The timeline for five level of automated vehicle which are recently available is from level 0 to level 2. The higher level which are level 3, 4 and 5 are expected to be

available on traffic in 2019 to 2020, 2021 to 2014 and 2025 respectively. Therefore, the various of market penetration is used to investigate in this study.

2.2 Work zone

Maintenance and rehabilitation for highway is necessary depends on its life cycle time. The construction work on roadway is called “work zone”. Lane closure and temporary traffic control are needed for traffic to pass the work zone safely. The model application of temporary traffic control which is used for simulation network in VISSIM is according to the most recent version of the Manual on Uniform Traffic Control (MUTCD) 2009 edition [16]. There are four components of temporary traffic control zone as follows:

- Advance warning area
- Transition area
- Activity area
- Termination area

According to the condition of simulation network of this thesis, figure 2 shows all the components of temporary traffic control zone which is used below. The advance warning area is the upstream of the work zone taper where the road users are informed about the upcoming work zone. The first warning sign should be placed at least 0.5 mile before the transition area on the freeway or expressway where driver’s speed generally exceeds 45 mph. The transition area is where the road user is channelized from normal path to the open way to pass through the work zone. This area is usually installed with the taper to control which its minimum length is calculated from the post speed and the width of offset of vehicle regarding to MUTCD in section 6C-3 [16]. Next, the activity area, it contains the work zone, both longitudinal and lateral buffer space, traffic

space and work space. Lastly, termination area is the section where road user returns to its normal path. This section also has downstream taper of 100 feet.

According to the work zone speed limit on freeway by FHWA, the work zone speed limit must not reduce the established speed limit by more than 15 mph and cannot be below 20 mph. On any roadway except divided highway, the maximum work zone speed limit shall not exceed 40 miles per hour. According to the condition of the simulated network of this study, the work zone speed limit should be 40 mph.

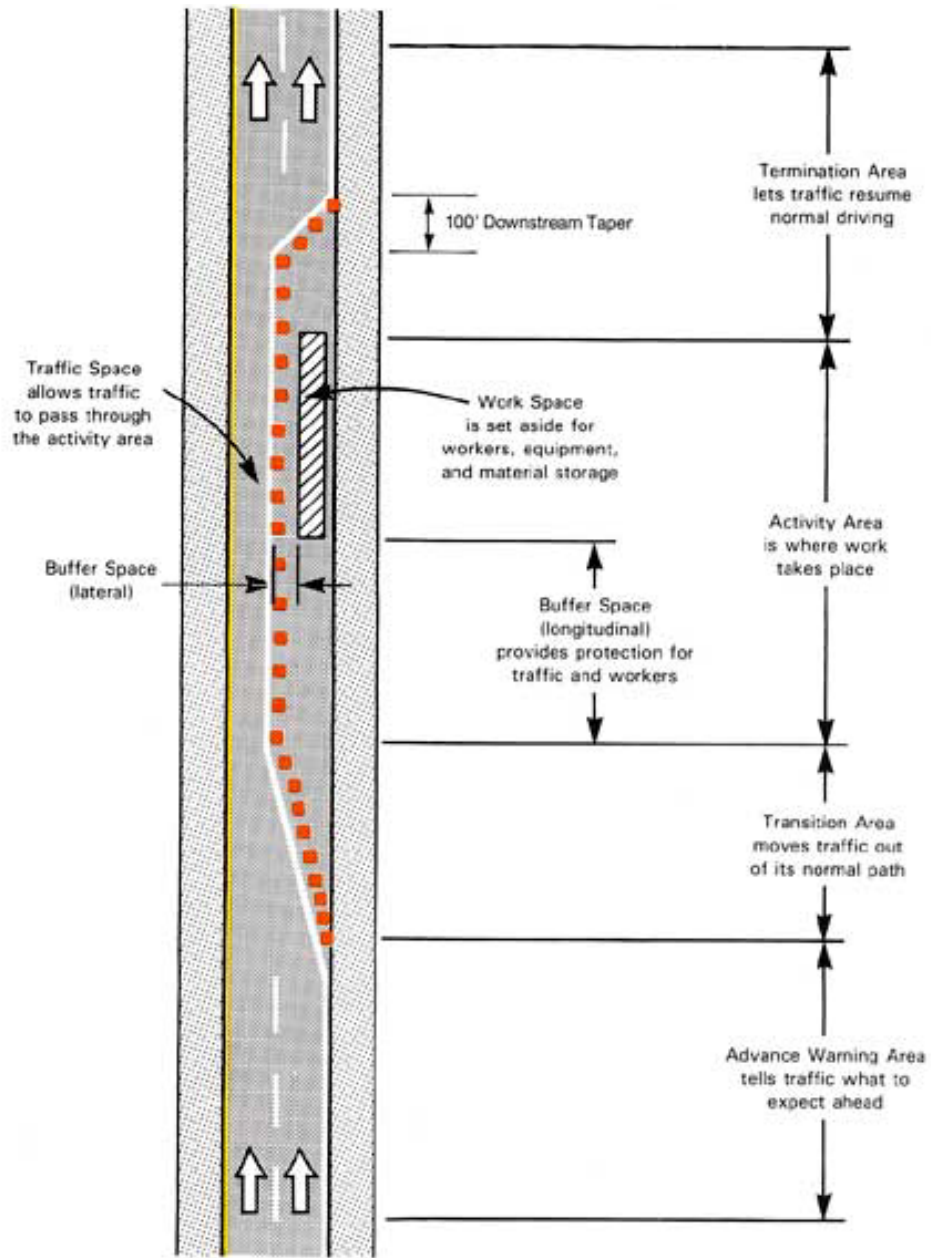


Figure 2: Component parts of a temporary traffic control zone [16]

2.3 Merging strategies

The process on traffic implementation to efficiently and safely merge and pass through the work zone could be done in many ways. There are two typical types of merge strategies which are early merge and late merge strategies. The vehicle merges before the merge point in the early merge strategy. In contrast, vehicle stays on its lane until the merge point for the late merge strategy. Both merge strategies could perform by static merge and dynamic merge techniques. The static merge technique is the most effective when there is steady flow. Meanwhile, the dynamic merge technique is more useful for the fluctuating traffic demands [17]. According to this study, early merge and late merge concepts with the static technique are used to performed in the simulation.

2.3.1 Early merge

The main concept of early merge is that vehicles are encouraged to merge into an open lane well in advance of the work zone taper. This concept allows time for vehicles to find a gap and complete the merging process before reaching the lane drop. This system breaks down with high demand and fewer gaps [18]. Early merge is efficient for low to moderate traffic demands [19] because when the capacity is reached, it would increase the risk of high speed driver to encounter the queue that is formed. Figure 3 shows the pattern of early merge.

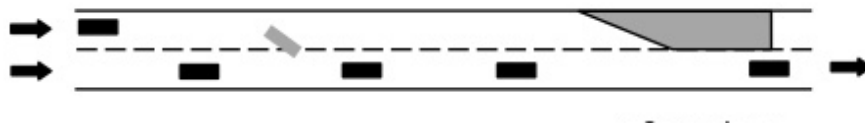


Figure 3: Early merge pattern

2.3.2 Late merge

The main concept of late merge is that vehicles are encouraged to merge into the open lane right before the work zone taper. This concept tries to take advantage of full capacity of the freeway approaching the work zone to minimize the length of queue formation when demand approaches capacity or when demand is high. The vehicles use all available lanes and take turn when they reach the merge point by performing alternating pattern. Delft University in Netherlands explained this pattern as a “Zipper” method. With the proper use of late merge could improve the vehicle throughput significantly and reduce the queue length up to 50 percent [20]. Figure 4 shows the pattern of late merge.



Figure 4: Late merge pattern

2.3.3 Static merging

Static merging uses static sign to instruct the vehicle on where to merge which is approximately one mile in advance. The static early merge strategy is not sensitive to the traffic condition in real time. The lane changing instruction remains the same regardless of the work zone traffic condition. The early static merging usually implemented by placing the advance warning sign prior to the work zone about 1 mile. For the static late merge strategy, which is not used in common, it is implemented by placing to sign instructing the vehicle to remain on its lane until the merge point. The sign could be the flashing sign which is activated at time regarding to the historical traffic data conditions. According to the simulation model of this study, the static merge is used with the assumption of low connectivity of level 3 automated vehicle. Therefore, both

manual vehicle and level 3 automated vehicle could be informed about where to start merging before or right at the lane drop.

2.3.4 Dynamic merging

Dynamic merging strategy could alternate between early merge and late merge due to the traffic at that time [17]. Therefore, the merge point moves along with the end of the queue. It uses the intelligent transportation system (ITS) to monitor the real-time traffic condition and to instruct the vehicle. The equipment used are such as changeable message sign or flashing sign. The changeable message sign could be used to change merging strategy between early merge and late merge. For the dynamic early merge, the merge point moves along with the end of the queue. Meanwhile, for the late merge, the changeable message sign either displays the late merge message or shows the blank message.

Most of the researches on dynamic lane merging strategy are done with the lane closures on roads which have two lanes of travel in one direction reducing to one lane or refers as 2-to-1 lane closure. The dynamic late merging works best when traffic volumes are in between 1,200 vphpl and 1,800 vphpl [21]. Another study suggests that it is better to use the late merging strategies when volumes are anything greater than 1,000 vehicles per hour [22]. One study stated that the dynamic late merge strategy is efficient when the percentage of heavy vehicles is greater than 20% due to their slow acceleration rates [23]. According to many studies, the best practice to implement varies regarding to different condition. Therefore, the study with the level 3 automated vehicle could be useful and could alleviate the level of study to the next level.

3. METHODOLOGY

This chapter introduces how the simulation network is set and how to investigate the result regards to the objective of this thesis. The simulation network is modeled by VISSIM microsimulation tool with 3 main scenarios of merging. The result of each scenarios is investigated and analyzed from vehicle throughput and travel time for the best practice of merging with many market penetrations of level 3 automated vehicle on 2-lane freeway entering the work zone area.

3.1 VISSIM Microsimulation Software

The scenarios investigated in this thesis are modeled by using VISSIM, a simulation modelling software developed by PTV, where it can analyze a time-step based approach to identifying opportunities for each vehicle within a network [24]. It is the advance microscopic simulation program for modeling multimodal transport operations. For driving behavior, it is control by longitudinal control and lateral controlled which are defined by car following model and lane changing model respectively.

3.1.1 Longitudinal Control

The longitudinal control of vehicle is considered with the changes in vehicle speed and response to vehicle in front of it which is defined by car following model. The available car following models in VISSIM are derived by Wiedemann in 1974 which are Wiedemann 74, Wiedemann 99 and no interaction car following model. Vehicle with no interaction car following model does not interact with any other vehicles [25] which is recommended to apply for pedestrian. The Wiedemann 74 car following model is suitable for urban traffic where interrupted traffic usually occurs. The Wiedemann 99 car following model is suitable for freeway traffic.

According to the objective of the research, it focuses on level 3 automated vehicle driving on freeway. Therefore, the Wiedemann 99 car following model is used. The basic concept of Wiedemann car following model is that the human driver of a faster moving vehicle starts to decelerate as the human driver reaches his individual perception threshold to a slower moving vehicle [25]. The speed of following vehicle is less than the leading one since human driver could not easily determine the speed of the leading vehicle. The various distribution of speed, slightly and steady acceleration and deceleration, and distance behavior are also considered in the model.

The Wiedemann model has been developed from four stage of driving conditions which are free driving, approaching, following and braking. The first stage, free driving, identifies a vehicle that does not need to respond to the proceeding vehicle. Human driver seeks to reach and maintain his desire speed which could be oscillated due to the imperfection throttle control by human. Moreover, this stage is defined as “free flow” in transportation engineering field. Secondly, in approaching condition, when trailing vehicle could acknowledge the existence of the leading vehicle, the trailing vehicle decelerate to adjust its speed to a lower speed than the speed of the leading vehicle. Therefore, it does not have difference in speed when the trailing vehicle reach its desire safety distance. Next, in the following condition, the distance from the trailing vehicle to the leading vehicle oscillates at least equal or more than the safety distance. The trailing vehicle drives without consciously accelerating and decelerating. The difference speed also oscillates around zero. Lastly, braking condition, this condition happens when the trailing vehicle moves closer to the leading vehicle. The trailing vehicle has to apply medium to high deceleration when the distance between vehicles is less than the desire safety distance. The rate of deceleration depends on how the leading vehicle change its speed or when there is another vehicle tries to

change the lane by squeezing in between the trailing and the leading vehicles. The accident is likely to occur at this stage.

The model is shown in figure 5 where it explains the six thresholds in these following models [26]. The y-axis or ΔV is the change in velocity between trailing and leading vehicles. The x-axis or ΔX is the change in distance between trailing and leading vehicles. The parameters shown in the graph are as follows:

- AX is the desired distance between two stationary vehicles
- BX is the minimum following distance which is considered as a safe distance by drivers
- CLDV is the point at short distances where drivers perceive that their speeds are higher than their lead vehicle speeds
- SDV is the points at long distances where drivers perceive speed differences when they are approaching slower vehicles
- OPDV is the points at short distances where drivers perceive that they are travelling at a lower speed than their leader
- SDX is the maximum following distance indicating the upper limit of car-following process.

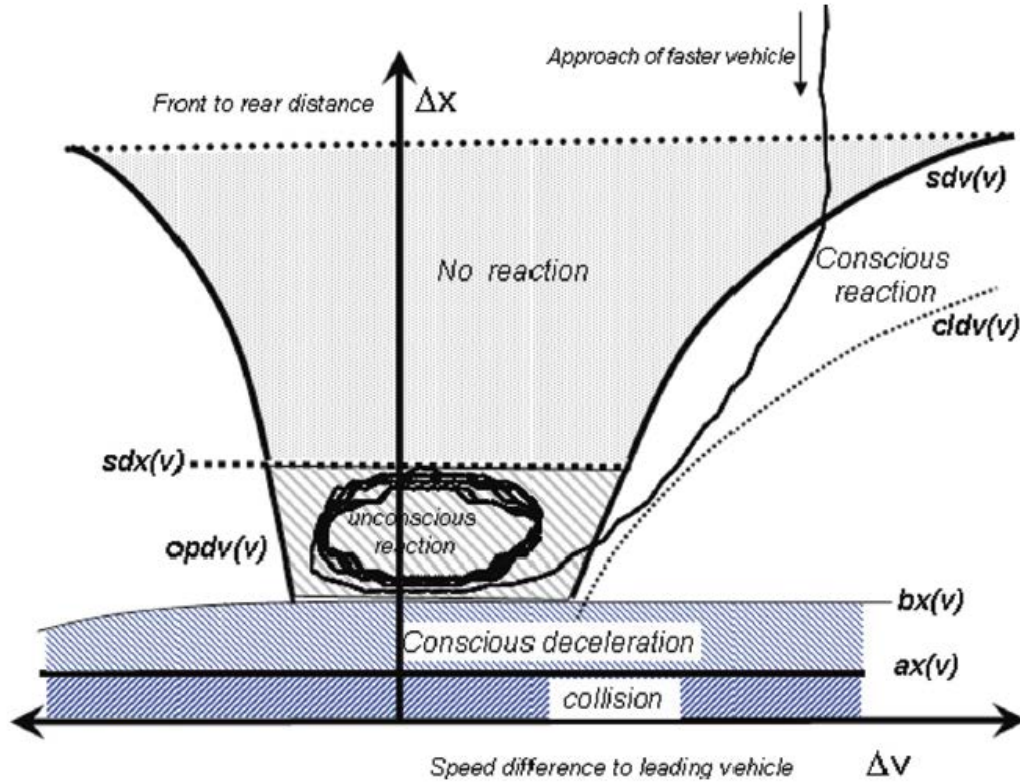


Figure 5: Wiedemann Car following model [27]

3.1.2 Wiedemann 99 Car Following Model

According to the simulation purpose, the simulation network is simulated by using the freeway. Therefore, the Wiedemann 99 car following model is used. It has ten parameters from CC0 to CC9 in the model. The default value is used for the manual vehicle. The parameters for level 3 automated vehicle could affect the car following model. For the objective of this study, the parameters for level 3 automated vehicle has changed according to the observations and studies as follows.

CC0 is the average standstill distance between two vehicles [25] which is the distance between the subject vehicle and the leading vehicle during times when the vehicles have stopped such as in traffic jam. The smaller value of CC0 allows smaller gaps between stopped vehicles.

The default value of CC0 is 4.92 feet. According to MotorTrend's latest testing, in general, most of the industries use a value of 9 feet of CC0 for observations. It is the roughly the lowest value for stopping distance from many of automotive manufacturers [28]. According to PTV Group, it is recommended to keep smaller stand still distances of CC0 for automated vehicle and the expectation that level 3 automated vehicle would perform better than human driver, a value of 4.92 feet is used instead of 9 feet in order to avoid the decreasing capacity from increasing gap distance.

CC1 or headway time is the time headway between the driving vehicle and leading vehicle which distributes regarding to the desire safety distance [25]. The higher the value, the more cautious the driver is. The safety distance is defined in the car following model as the minimum distance that a driver will maintain while following another vehicle. Both CC0 and CC1 can determine the aggressiveness of the subject vehicles from the safety distance, which defined as minimum distance between vehicles, by $dx_{safe} = CC0 + CC1 * v$. The default value of CC1 is 0.90 second. According to the MotorTrend's latest testing results, semi-automated vehicles could follow the leading vehicles with the headway as small as 0.70 second. The headway time parameter in VISSIM cannot be set as 0.7 second and 0.5 second could be too low to assume. Therefore, the value of 0.9 second is chosen for this simulation model.

CC2 or following variation is used to restrict the distance difference (longitudinal oscillation) or how much more distance than the desired safety distance the driver allows before he intentionally moves closer to the car in front [25]. It affects how well the subject vehicle responds to leading vehicle's speed oscillation. The default vale of CC2 is 13.12 feet. According to MotorTrend's testing, the tested vehicles have an acceleration delay as small as 0.60 seconds from standstill condition [28]. Based on the science of car following of these vehicles, radar

adaptive cruise control, the distance difference can be calculated 4.4 feet. Therefore, a value of 4.4 feet will be used for CC2 for this simulation model to allow for shorter vehicle gaps.

CC3 or threshold for entering following controls the start of the deceleration process such as the second before reaching the safety distance [25]. The driver performs an approaching condition where this parameter controls the time that takes from free driving condition to following condition. The default value of CC3 is -8.00 seconds. According to the sensitivity analysis study of VISSIM driver behavior on highway capacity, this parameter should be changed dynamically with the speed of vehicle and has no significant impact on the capacity [29]. Therefore, the default value of -8.00 seconds is used in this simulation model.

CC4 or negative following threshold is the negative speed difference during the following condition [25]. It controls the sensitivity of driver reaction to the acceleration or deceleration of leading vehicle. Lower value of CC4 causes more sensitive reaction. The default value of CC4 is -0.35 ft/sec. For the level 3 automated vehicle, throttle pedal is not controlled by human driver which means that the speed of vehicle does not oscillate a lot. Therefore, a value of -0.10 ft/sec is used for this simulation model.

CC5 or positive following threshold is the positive speed difference during the following condition which the value of CC5 should be the opposite to the value of CC4 [25]. According to the reason of affect from CC4, higher value of CC5 could cause less sensitive reaction. The default value of CC5 is 0.35 ft/sec. The opposite value of CC4 which is -0.10 ft/sec is used for CC5 in this simulation model.

CC6 or speed dependency of oscillation is the parameter that defines how the subject vehicle's speed oscillates based on the difference in distance between subject vehicle and leading

vehicle in the following condition. Larger value of CC6 causes greater speed oscillation with increasing distance between subject vehicle and leading vehicle increase. The zero value of CC6 causes the speed oscillation to be independent from the distance between subject vehicle and leading vehicle. The default value of CC6 is 11.44 1/m·s. According to the observation from industry, the radar adaptive cruise control follows the leading vehicle from a set headway time which cause the high degree of speed oscillation. The high value of CC6 is considered as a high level of oscillation [29]. According to the reason that there has no specific investigation for the exact value of CC6 for level 3 automated vehicle, the default value of 11.44 1/m·s of CC6 is used for this simulation model.

CC7 or oscillation acceleration is the rate of acceleration which defines how the speed oscillates during acceleration. It controls the level of speed oscillation produced by driver whether it is gentle and gradual or sudden and violent [29]. The default value of CC7 is 0.82 ft/sec². A larger value of CC7 causes greater oscillation during acceleration. According to MotorTrend's testing result, the speed oscillation could be higher than typical human driver (Kim, 2016). Moreover, CC7 with a value of 0.50, 1.00 and 1.50 ft/sec² represent small, medium and high values of oscillation respectively [29]. Therefore, a value of 1.25 of CC7 is used for simulation model.

CC8 or standstill acceleration is the desired acceleration rate of subject vehicle from standstill condition or when the subject vehicle's speed is zero [25]. The default value of CC8 is 11.48 ft/sec². According to MotorTrend's testing result, the standstill acceleration rate is approximately as low as 6.0 ft/sec², which is significantly less than the default value [28]. A lower level of CC8 could cause a significant negative impact on capacity [29]. Applying automated vehicle on roadway is expected to improve the roadway capacity. Therefore, the value of 11.48 ft/sec² is used for CC8 in this simulation model to avoid this negative impact.

CC9 or acceleration with 50 mph is the desired acceleration rate of subject vehicle when the vehicle speed is at 50 mph [25]. The default value of CC9 is 4.92 ft/sec². According to MotorTrend's testing result, the rate of acceleration from 50 mph is about 4.80 ft/sec². Therefore, the value of 4.80 ft/sec² is used for CC9 in this simulation model.

For better understanding on car following parameters, the explanation of the relationships of first seven parameters (CC0 – CC6) could be demonstrated in the following equations [26]. The equations are related to the graph shown in figure 5 where the variables are also shown. The equations are listed as follows

- $ax(v) = L + CC0$, where L is the length of leading vehicle.
- $bx(v) = ax(v) + CC1 \cdot v$, where v is equal to subject vehicle speed if it is slower than the lead vehicle; otherwise, it is equal to lead vehicle speed with some random errors. The error is determined randomly by multiplying the speed difference between the two vehicles by a random number between -0.5 and 0.5.
- $sdx(v) = bx(v) + CC2$ and $sdv(v)_i = -\Delta x - sdx(v)_i/CC3 - CC4$, Where Δx is the space headway between the two successive vehicles calculated from front bumper of the leading vehicle to front bumper of the subject vehicle.
- $cldv(v) = -\left(\frac{CC6}{17000}\right) (\Delta x - L)^2 - CC4$ and $opdv(v) = -\left(\frac{CC6}{17000}\right) (\Delta x - L)^2 - \delta(CC5)$,

Where δ is a dummy variable which is equal to 1 when the subject vehicle speed is greater than CC5 and δ is equal to 0 if subject vehicle speed is not greater than CC5.

The parameter CC7 to CC9 are the acceleration rates which depend on the programmed performance of vehicle, the difficulty of human driver to press the accelerator or the mechanical capabilities of the vehicle which could not derived from equations.

For summary, table 1 concludes the model the parameters of longitudinal control in car following model for manual vehicle and the calibration values for the level 3 automated vehicle which are used VSSIM microsimulation model. All the modified parameters for level 3 automated vehicle are highlighted in bold in the table. In addition, the default value is set for all the other parameters that has not been mentioned.

Table 1: The set value of parameters in VISSIM microsimulation model

Wiedemann 99 Car Following Parameter	Default value for manual vehicle	Calibrated value for level 3 automated vehicle
CC0	4.92 ft	4.92 ft
CC1	0.90 s	0.90 s
CC2	13.12 ft	4.40 ft
CC3	-8.00 s	-8.00 s
CC4	-0.35 ft/s	-0.10 ft/s
CC5	0.35 ft/s	0.10 ft/s
CC6	11.44 1/m·s	11.44 1/m·s
CC7	0.82 m/s ²	1.25 m/s²
CC8	11.48 ft/s ²	11.48 ft/s ²
CC9	4.92 ft/s ²	4.80 ft/s²

3.1.3 Lane Change and Lateral Control

The lateral control of vehicle controls at the perpendicular direction of the vehicle travel direction. VISSIM divides the application for lane changing to “necessary lane change” in order to reach the next connector of a route and “free lane change” if there is more space and higher speed is required [25]. For necessary lane change, the driving behavior parameters contain the maximum acceptable deceleration for the subject vehicle and its trailing vehicle on the new lane. The deceleration depends on the distance to the emergency stop position of the next route

connector. For free lane change, VISSIM checks the desired safety distance to the trailing vehicle on the new lane. The desired safety distance depends on the speed of the vehicle that wants to change the lane and on the speed of the vehicle preceding it.

According to this study purpose, lane changing behavior of vehicles is significantly important for the analysis. The automated vehicle is expected to have a better lane change than manual vehicle [30]. Therefore, some lane change parameters in VISSIM is adjusted for a reasonable amount for the level 3 automated vehicle by ten percent. The default values are also set for the manual vehicle. The aggressiveness of lane changing could be adjusted by changing the safety distance which is used to specify car following behavior. For both types of lane change, a suitable gap in the direction of travel is needed where the gap size depends on speed of the vehicle changing the lane and speed of the vehicle approaching from behind on the lane [25].

Therefore, the minimum headway is reduced from 1.64 feet to 1.48 feet to allow smaller acceptable gap distance between two vehicles after a lane change. The safety reduction factor is reduced from 0.60 to 0.54 to allow a smaller acceptable safety distance of lane-changing vehicle and trailing vehicle when changing the lane. The default value of 0.60 reduces the safety distance by 40% which is change to 0.54 or 66% reduction. Thus, vehicle could be more aggressive due to the smaller gap size. The maximum deceleration for cooperative braking is reduced from -9.84 ft/s^2 to -10.48 ft/s^2 to allow more lane-change vehicle to move into its lane with heavier rate of braking. The higher the value, the stronger the braking and greater the probability of lane change.

In general behavior, the slow lane rule is set to allow overtaking of vehicle from the other lane. Advance merging feature is checked to allow more vehicle to change lane earlier. Moreover, the cooperative lane change feature is checked for more realistic behavior of lane change of

vehicle. In conclusion, table 2 summarizes the adjusted parameters of the lane change behavior type as shown.

Table 2: Adjusted value of lane change parameters

Lane change parameter	Default value	Adjusted value for level 3 automated vehicle
Minimum headway	1.64 ft	1.48 ft
Safety distance reduction factor	0.6	0.54
Maximum deceleration cooperative braking	-9.84 ft/s ²	-10.82 ft/s ²
Slow lane rule		Checked
Advance merging		Checked
Cooperative lane change		Checked

3.2 Simulation Network

3.2.1 Assumptions

General assumptions are made to this study simulation network as follows:

- The simulated traffic in subject freeway is only passenger vehicle, no truck and heavy vehicle on this freeway segment. Therefore, there are two types of vehicle which are manual vehicle and level 3 automated vehicle with the same vehicle model but different driving behavior.
- Level 3 automated vehicle is assumed to have low connectivity level in order to be informed about the location that need to merge at the first advance warning sign in an early merge scenario.
- No occasional control from human driver on level 3 automated vehicle during the simulation.

- The adjusted parameters for level 3 automated vehicle could affect the whole car following model. The investigation on level 3 automated vehicle recently does not have a typical standard. Therefore, the better investigation on level automated vehicle and adjusted car following model could be provided.
- According to the work zone length and speed impact on freeway, speed difference between vehicles and the speed in work zone could affect the capacity of freeway [31]. Therefore, the speed in work zone and the reduce speed area before entering the work zone is neglect in order to observe only the impact of level 3 automated vehicle on merging.
- The traffic in the simulation model is mix traffic on both lane. The level 3 automated vehicle and manual vehicle travel concurrently on 2-lane freeway.
- Traffic flow in each simulation is the traffic demand on each lane which is defined in vehicle per hour per lane.
- Queue jumping and lane straddling are ignored and assumed to not occur in this simulation.
- The weather condition and road surface condition of the freeway segment is normal except for the work zone area. Therefore, the weather effect and the roughness of road surface are not considered.
- No malfunction of vehicle exists or occurs on this freeway segment during the simulation.

3.2.2 Simulation network model

The simulation network is created in VISSIM with two type of vehicles which are manual vehicle and level 3 automated vehicle. The simulation network is a straight 2-lane freeway with 6 miles long. The traffic is in one direction on two lanes eastbound. It has 12 feet width on each lane regards to AASHTO green book [32]. The freeway contains 2-to-1 lane drop beginning at

4 miles from start point of the freeway. The desired speed for vehicle is 70 mph regarding to the speed limit of freeway in Wisconsin.

The driving behaviors that could cause significant impact on freeway capacity are the queue jumping and lane straddling [33]. Queue jumping is when a driver already in the open lane decides to change lane for a better position by moving to the closing lane and passes one or more vehicles before merging back into the open lane. Lane straddling is when a driver intentionally places their vehicle across portions of both the open and closing lane to prevent other vehicles behind them to pass and merge ahead of it. However, those driving behaviors are ignored and not occur in this simulation study.

The 2-to-1 lane drop on freeway is designed followings the standard of work zone traffic control plan of Manual on Uniform Traffic Control (MUTCD) version 2012 [16]. The temporary traffic control zone includes the entire section of roadway between the first advance warning sign through the last traffic control device as shown in figure 2 of chapter 2. It begins with advance warning area, transition area, activity area and termination area respectively.

According to MUTCD on section 6C-1, the advance warning sign is placed at least from 500 feet to half mile before the temporary traffic control zone for the freeway which vehicle speed generally high and exceeds 45 mph [16]. Therefore, the first advance warning sign in this simulated network is placed at 1 mile or 5,280 feet before the taper. Next, in transition area, traffic must be channelized from the normal path to a new path which usually uses taper to control the traffic. According to section 6C-3 of MUTCD, for freeways, expressways, and other roadways having a speed of 45 mph or greater, the minimum length for merging tapers should be computed by a formula $L = W \times S$, where W is the lateral shift of traffic in feet and S is the posted speed [16]. Therefore, the taper length of this simulation network is:

$$L = 12 \text{ feet} \times 70 \text{ mph} = 840 \text{ feet}$$

In these regards, the taper length is 840 feet connecting to the activity area. Since this research focuses on the impact of merging only, the buffer space in activity area and the termination area is ignored. The work zone and the buffer zone which are in the activity area is involved in one lane segment with a total of 1,560 feet and then expands into two lanes with another mile of termination area with 100 feet of downstream taper. The total of activity area is equal to 2,500 feet. Moreover, the work zone speed limit is 40 mph according to the FHWA. The reduce speed area is implemented in the simulation network along the activity area which starts from the end of the upstream taper to the end of the beginning of the downstream taper. Figure 6 and figure 7 show the simulation network created in VISSIM with length of each area and the location of each detector in sketch picture and in VISSIM respectively. Note that the figures shown are not to scale.

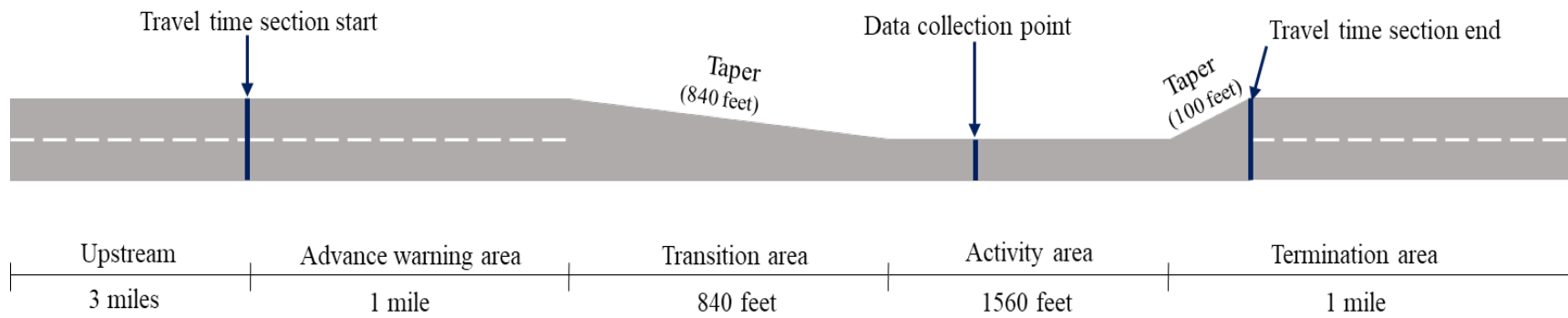


Figure 6: Simulation network and scale



Figure 7: Simulation network in VISSIM

3.3 Simulation scenarios

There are three major scenarios for this study which are early merge, late merge and hybrid scenarios. Each of the major scenarios is divided by the market penetration of level 3 automated vehicle and the traffic flow.

Firstly, the early merge scenario, level 3 automated vehicle on the closure lane could merge to the open lane once it passes the advance warning sign whenever it finds enough gap to change lane. It merges upstream before it reaches the merge point to avoid lane drop. No vehicle using the lane about 1,000 feet of the closed lane before the merge point because vehicle tries to merge into the open lane before the merge point. The scenario is performed by modifying the values of emergency stop distance of the connector connecting the work zone and freeway. Moreover, the lane change distance on the open lane is set with the length which is longer than the first advance warning sign to avoid queue jumping and lane straddling.

Secondly, late merge scenario, all vehicles remain on their lane until they reach the merge point at lane drop. Vehicles is fully using the freeway on both lanes and start to merge at the merge point. The vehicle on the open lane allows the vehicle on the left lane to merge one by one with alternative pattern or as known as “Zipper”. No lane change feature is set to perform this scenario which allow vehicle to remain on its lane until the merge point.

Lastly, hybrid scenario, vehicle starts to merge whenever it finds the acceptable gap once it passes the advance warning sign. It continues driving to the merge point at lane drop if it could not find any gap and performs alternate pattern with the vehicle on the open lane. This scenario is the combination of the early merge and late merge scenarios. Moreover, the lane change distance on the open lane is set with the length which is longer than the first advance warning sign to avoid

queue jumping and lane straddling. Figure 8 shows the comparison of vehicles perform in each scenario as follows:

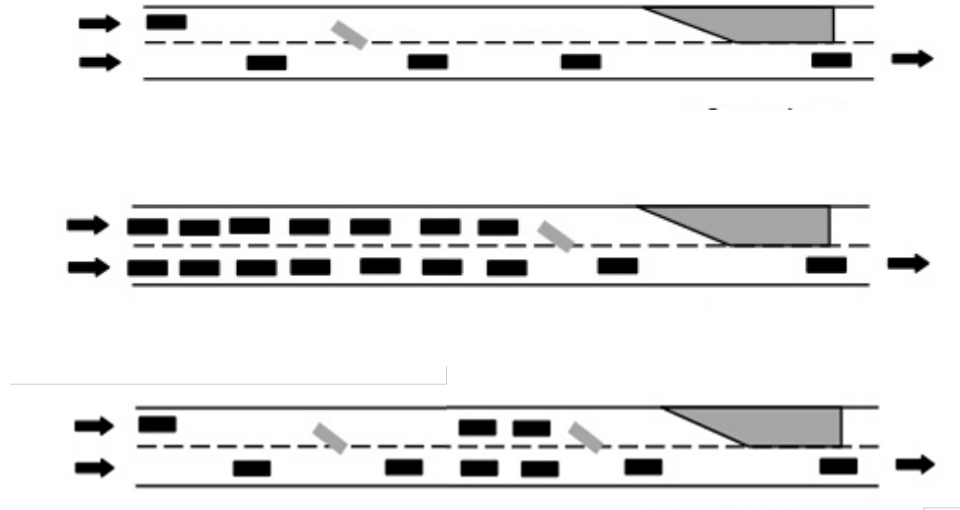


Figure 8: Comparison of three merge strategies

To simulate each scenario for the impact of level 3 autonomous on merging at lane drop, the simulation is performed with the different traffic flow and market penetration of level 3 automated vehicle. The traffic flow varies from 1,000 veh/hr/ln to 2,000 veh/hr/ln with the increment of 200 veh/hr/ln for each simulation. The market penetration varies from 40 percent to 100 percent with the increment of 20 percent for each simulation. Moreover, the zero market penetration or the traffic with all manual vehicle is performed in the simulation in order to compare the difference with the mix traffic. To be concluded, the total of 90 simulations are performed which is explained in the next section.

3.4 Procedure and Data collection

To perform the simulation of each scenarios by VISSIM, after creating the simulation network and specify vehicle types and behaviors, perform all the simulation with different merging

scenarios with different traffic flow and market penetration. A total of 90 simulation scenarios is performed as shown in figure 9. Each simulation perform ten simulation runs with random seeds of 7, 16, 25, 34, 43, 52, 61, 70, 79 and 88.

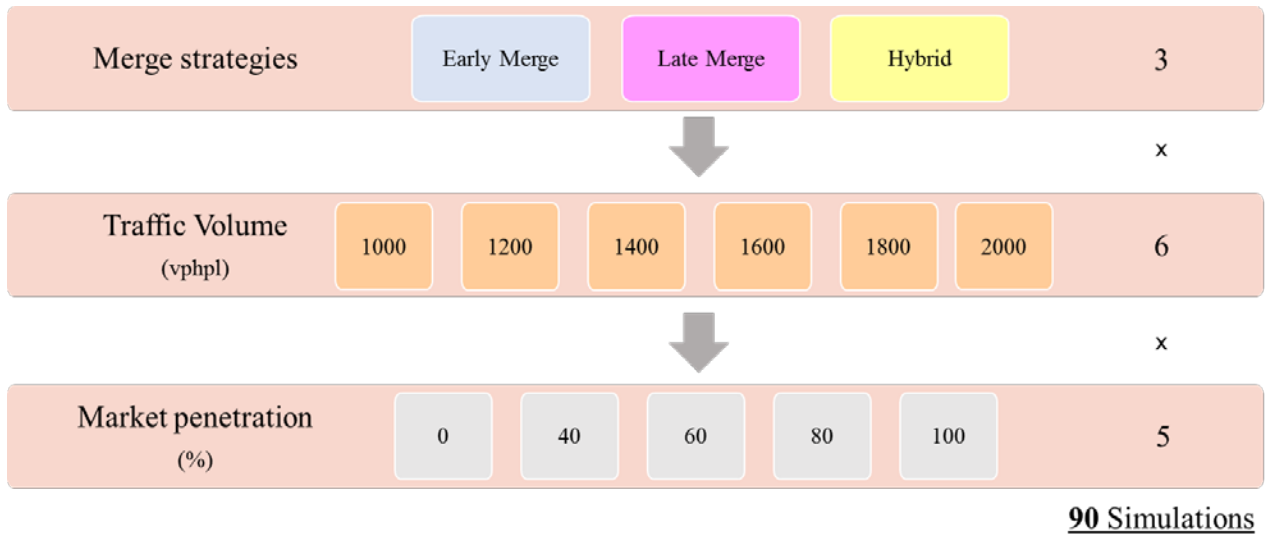


Figure 9: Simulation scenarios

For measuring the impact of level 3 autonomous on merging into 2-to-1 lane drop, two types of measurement are used. First, the vehicle throughput which is collected from the data collection in VISSIM at the open lane which is placed 500 feet behind the merge point of lane drop. The vehicle throughput is the number of vehicle that passing through the open of the activity area of the work zone per hour. The other performance measure is the vehicle travel time which starts from the beginning of advance warning area and ends at the beginning of termination area of the work zone. Vehicle travel time is measures in seconds.

The simulation period is 65 minutes with a warm up time of 5 minutes. The data is collect from the first five minutes until the last minute of the simulation period which is 1 hour. The ten results of vehicle throughput and travel time from each simulation is averaged. The larger vehicle

throughput at each traffic flow and market penetration in each merging scenario is considered the best practice among the three major scenarios. The travel is also used to help in consideration.

4. RESULTS AND ANALYSIS

4.1 Results

The total of 90 simulations gave the results vehicle throughput and vehicle travel time. Table 3 to table 8 show the conclusion of the vehicle throughput and travel time from all simulations in each scenario respectively.

Table 3: Vehicle throughput from early merge scenario

Traffic flow (vphpl)	Market penetration (%)				
	0	40	60	80	100
1000	1960	1965	1968	1969	1969
1200	2269	2328	2354	2361	2362
1400	1899	1958	2053	2184	2288
1600	1871	1994	2039	2048	2101
1800	1847	2017	2019	2037	2079
2000	1849	2025	2035	2041	2093

Table 4: Vehicle throughput from late merge scenario

Traffic flow (vphpl)	Market penetration (%)				
	0	40	60	80	100
1000	1958	1964	1964	1965	1966
1200	2015	2018	2041	2052	2127
1400	2027	2035	2039	2073	2133
1600	2010	2020	2020	2076	2141
1800	2020	2024	2032	2075	2142
2000	2029	2041	2042	2072	2143

Table 5: Vehicle throughput from hybrid scenario

Traffic flow (vphpl)	Market penetration (%)				
	0	40	60	80	100
1000	1962	1964	1969	1969	1969
1200	2339	2343	2361	2362	2364
1400	2091	2237	2262	2278	2313
1600	1962	2007	2011	2097	2188
1800	1866	2002	2076	2079	2200
2000	1931	2051	2077	2103	2214

Table 6: Travel time from early merge scenario

Traffic flow (vphpl)	Market penetration (%)				
	0	40	60	80	100
1000	99.22	98.20	98.08	98.09	98.09
1200	139.88	117.33	109.00	105.01	103.77
1400	384.06	325.56	326.41	295.66	282.81
1600	419.96	418.13	417.25	405.11	403.32
1800	442.74	437.72	420.36	416.43	405.49
2000	460.92	441.41	437.38	434.98	424.09

Table 7: Travel time from late merge scenario

Traffic flow (vphpl)	Market penetration (%)				
	0	40	60	80	100
1000	111.01	109.15	110.58	107.90	102.34
1200	413.89	401.94	335.99	332.59	284.77
1400	487.29	494.90	491.71	490.50	456.35
1600	535.59	532.88	530.37	528.12	520.86
1800	570.31	569.77	569.20	564.56	537.83
2000	591.43	574.86	571.90	555.68	533.91

Table 8: Travel time from hybrid scenario

Traffic flow (vphpl)	Market penetration (%)				
	0	40	60	80	100
1000	98.81	98.00	98.14	98.09	97.80
1200	133.98	108.48	105.59	105.35	103.74
1400	333.75	286.64	275.31	273.88	273.18
1600	472.05	478.79	468.52	439.63	439.02
1800	520.45	509.49	513.04	487.56	476.36
2000	561.63	544.30	535.38	503.07	470.72

The results have shown noticeable similar trends for all three major scenarios. In general, the number of vehicle throughput should be increased when the traffic flow is increasing. Moreover, the travel time should be increase due to the increasing density of roadway which could cause congestion. Furthermore, as the market penetration of level 3 automated vehicle increases, the number of vehicle is increased at each flow. In contrast, the vehicle travel time at each traffic decreases when market penetration increases. From the results, the higher market penetration of level 3 automated vehicle could improve the mobility performance of vehicle passing through the work zone on 2-to-1 lane drop freeway by increasing the vehicle throughput and decreasing the travel time. The detail of analysis and the best practice of merging strategies are discussed in the next section. Therefore, the graphs are plotted to show the relation between vehicle throughput and travel time with different traffic flow and different market penetration for all three merging strategies as shown in figure 10 to figure 31.

4.2 Analysis

In general, the number of vehicle throughput would increase or decrease follows the traffic flow at all market penetration of level 3 automated vehicle. In a big picture, all three scenarios which are early merge, late merge and hybrid have the same trend of higher vehicle throughput and lower travel time with the increase of market penetration of level 3 automated vehicle. According to the different strategy on merging of each scenario, some strategy could perform better at different traffic flow.

4.2.1 Vehicle throughput

4.2.1.1 Vehicle throughput and traffic flow at each market penetration

For the first performance measurement, the number of vehicle throughput is compared between each merge scenario regarding to each traffic flow and each market penetration. Figure 10 to figure 14 show the relation between vehicle throughput and traffic flow at each market penetration for all three merging strategies as follows:

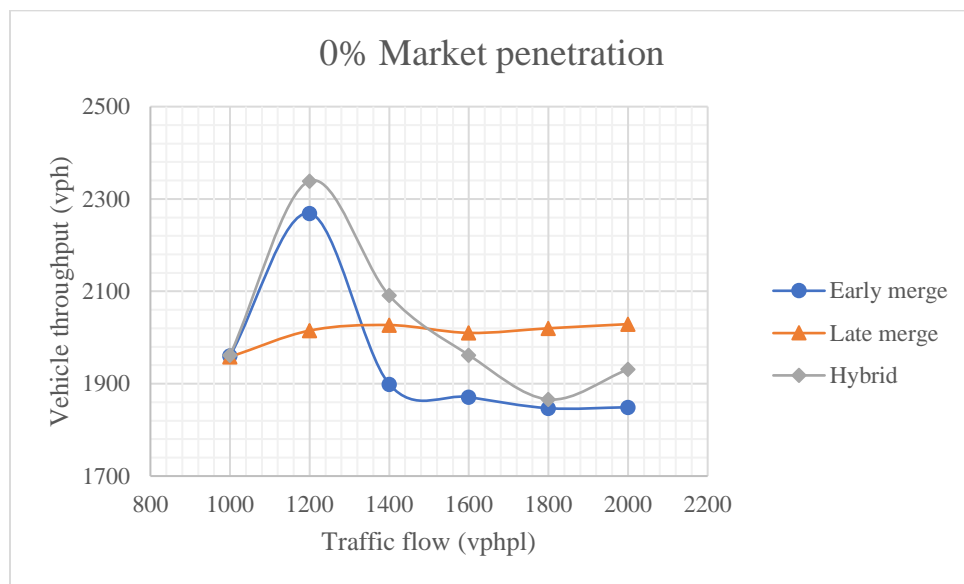


Figure 10: Relation between vehicle throughput and traffic flow at 0% market penetration

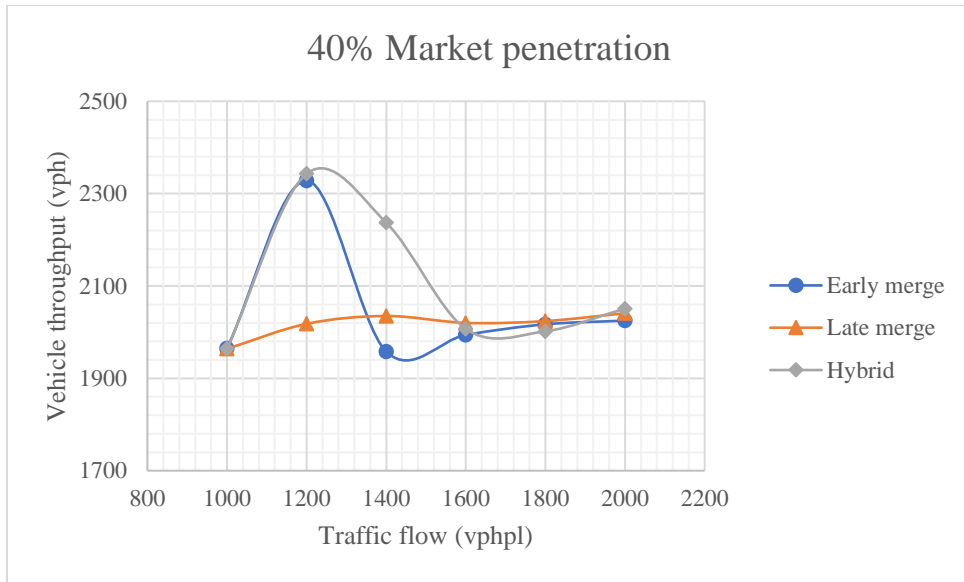


Figure 11: Relation between vehicle throughput and traffic flow at 40% market penetration

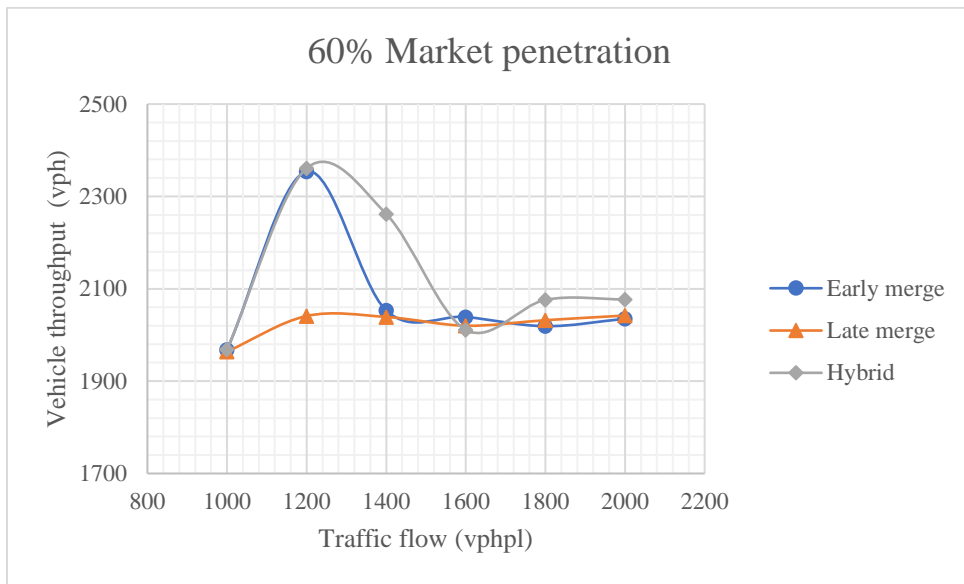


Figure 12: Relation between vehicle throughput and traffic flow at 60% market penetration

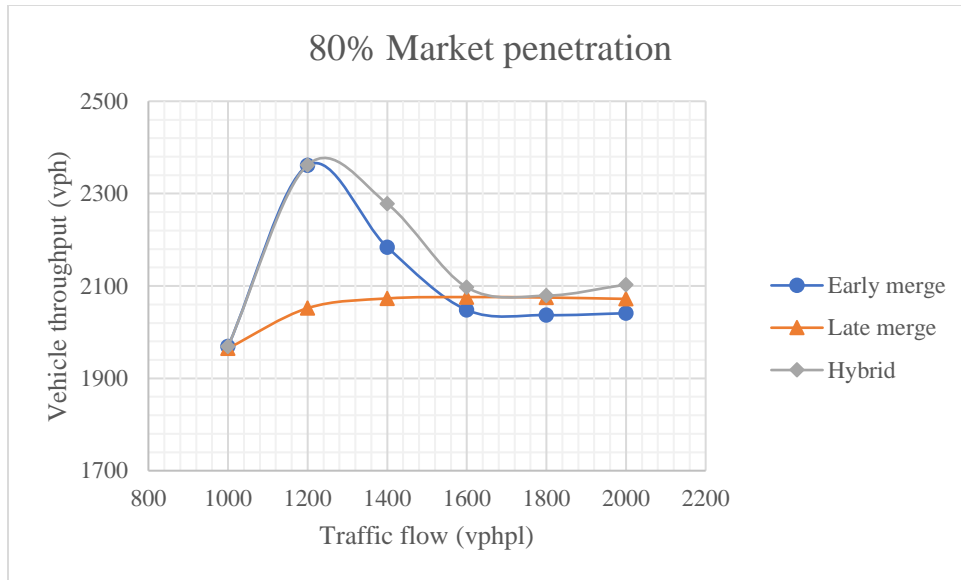


Figure 13: Relation between vehicle throughput and traffic flow at 80% market penetration

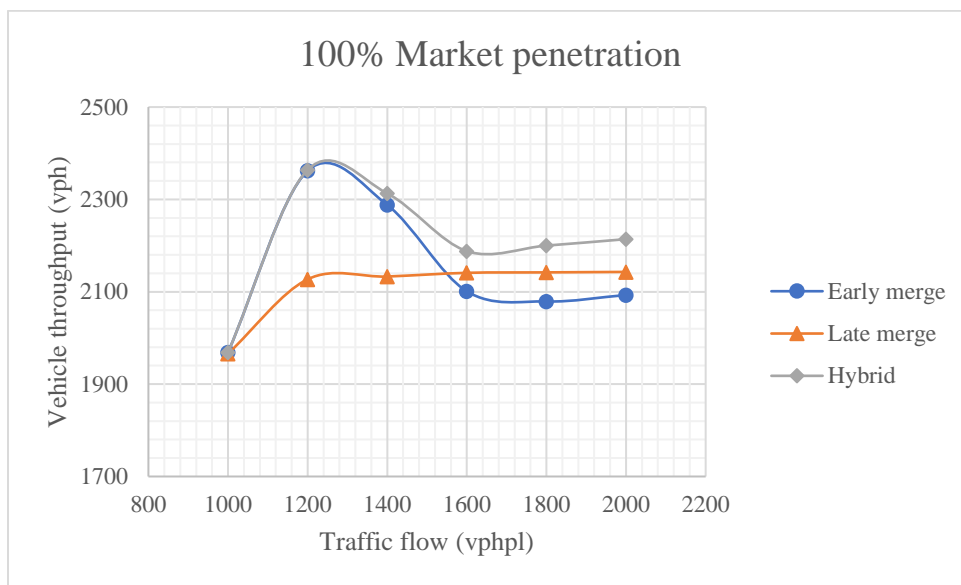


Figure 14: Relation between vehicle throughput and traffic flow at 100% market penetration

According to the results shown, the vehicle throughput of both early merge and hybrid strategies significantly drop at the traffic flow between 1,200 vphpl to 1,600 vphpl and slightly increase at higher traffic flow. Moreover, the vehicle throughput from hybrid strategy is mostly higher than early merge strategy at all cases. The vehicle throughput of early merge strategy starts to be higher than late merge strategy approximately at 1,400 vphpl at 0% and 40% market

penetrations. Meanwhile, at 60% to 100% market penetrations, the vehicle throughput of early merge strategy starts to be higher than late merge strategy at about 1,600 vphpl. Moreover, the vehicle throughput of early merge strategy at higher traffic flow than 1,600 vphpl is notably higher than late merge strategy at zero market penetration but comes closer with a little lower vehicle throughput than of late merge at higher market penetration. The better car following and lane change behavior of level 3 automated vehicle could improve the number of vehicle throughput with the better lane change in this strategy. Therefore, the capacity drop could occur slower at higher traffic flow and has higher vehicle throughput from higher market penetration of level 3 automated vehicle.

For late merge strategy, the vehicle throughput is almost constant and slightly increases at high traffic flow for all of the market penetration of level 3 automated vehicle. The reason for constant vehicle throughput at all market penetration and traffic flow could be because of the zipper merge pattern. Vehicle could pass through the merge point with constant rate and could slightly increase with higher market penetration of level 3 automated vehicle. Thus, the car following and lane change behavior are not performed freely on roadway due to the condition that vehicle needs to keep queue up and merge at the merge point. The better performance of late merge strategy at high traffic flow at 0% penetration causes from the full capacity of roadway that has been used, but when the traffic is mixed with higher market penetration of level 3 automated vehicle, it has almost equal and lower performance with the early merge and hybrid strategies respectively. The amount of vehicle throughput of late merge when it starts to perform zipper merge pattern is averaged from 2,050 vphpl to 2,065 vphpl with different market penetration of level 3 automated vehicle.

For hybrid strategy, it has lower vehicle throughput than late merge strategy only at the low market penetration even it has a capacity drop between traffic flow of 1,200 vphpl to 1,600 vphpl. The traffic break down on freeway could occur when it starts to reach its capacity [34]. Meanwhile, it has higher vehicle throughput than early merge strategy at almost all cases. The better performance of hybrid strategies could be because of the better driving behavior of level 3 automated vehicle and with the strategy used. Vehicle could merge whenever it finds the acceptable gap before the merge point and can continue to perform the zipper at the merge point if it cannot find the gap earlier. For the same reason of better driving behavior of level 3 automated vehicle, vehicle throughput of 0% penetration is lower than late merge at high traffic flow, but when higher market penetration of level 3 automated vehicle is mixed in the traffic, it has greater vehicle throughput than late merge at higher traffic flow.

In summary, the hybrid strategy is the best practice to use regarding to the amount of vehicle throughput when there is mix traffic of level 3 automated vehicle. At traffic flow lower than 1,600 vphpl, the hybrid strategy has significantly higher vehicle throughput than late merge strategy. At higher traffic flow of 1,600 vphpl, it also has slightly higher vehicle throughput than late merge. Comparing to early merge strategy, it has lower vehicle throughput than late merge at higher traffic flow even it has higher vehicle throughput than late merge at lower traffic flow of approximately 1,400 vphpl. The early merge strategy could not perform better than late merge strategy because it does not use the full capacity of the roadway as late merge strategy. Hybrid strategy is the best since it combines both strategies of early merge and late merge. At low traffic flow, vehicle could perform early merge strategies which has significantly higher vehicle throughput. Meanwhile, when the traffic flow gets higher, vehicle that cannot find the acceptable

gap to change lane could continue moving to the merge point and perform late merge strategy or zipper merge pattern.

4.2.1.2 Vehicle throughput and market penetration at each traffic flow

Figure 15 to figure 20 show the relation between vehicle throughput and traffic flow at each market penetration for all three merging strategies as follows:

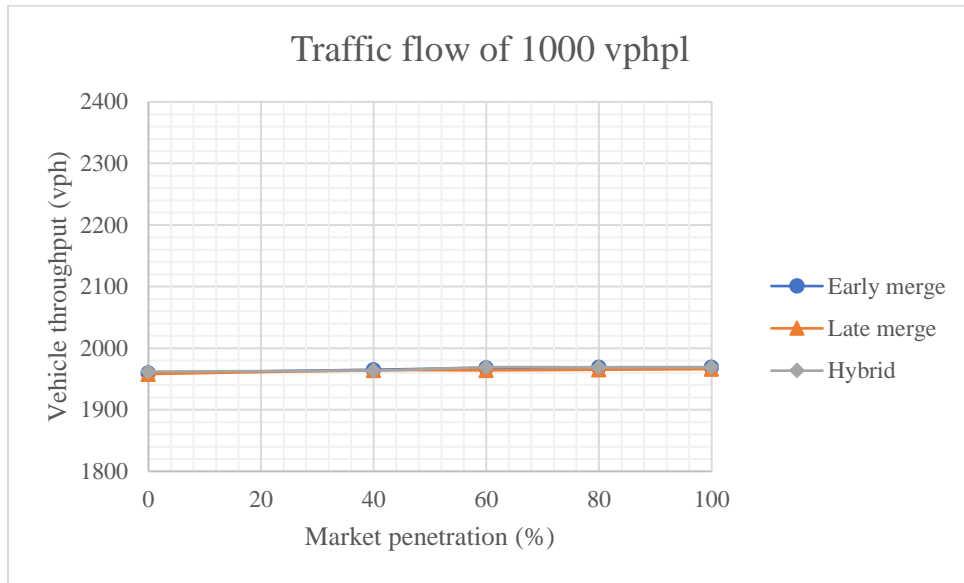


Figure 15: Relationship between vehicle throughput and market penetration at 1,000 vphpl

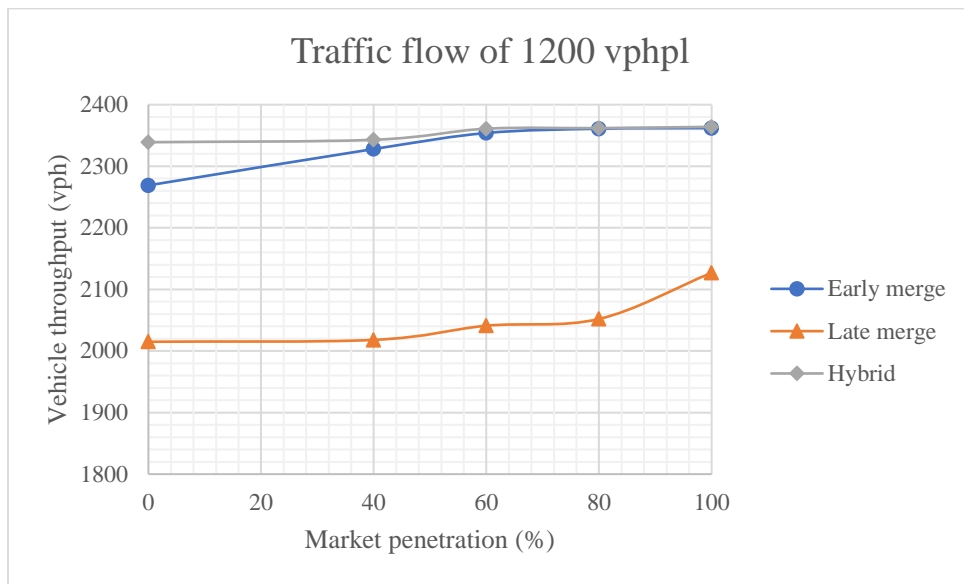


Figure 16: Relationship between vehicle throughput and market penetration at 1,200 vphpl

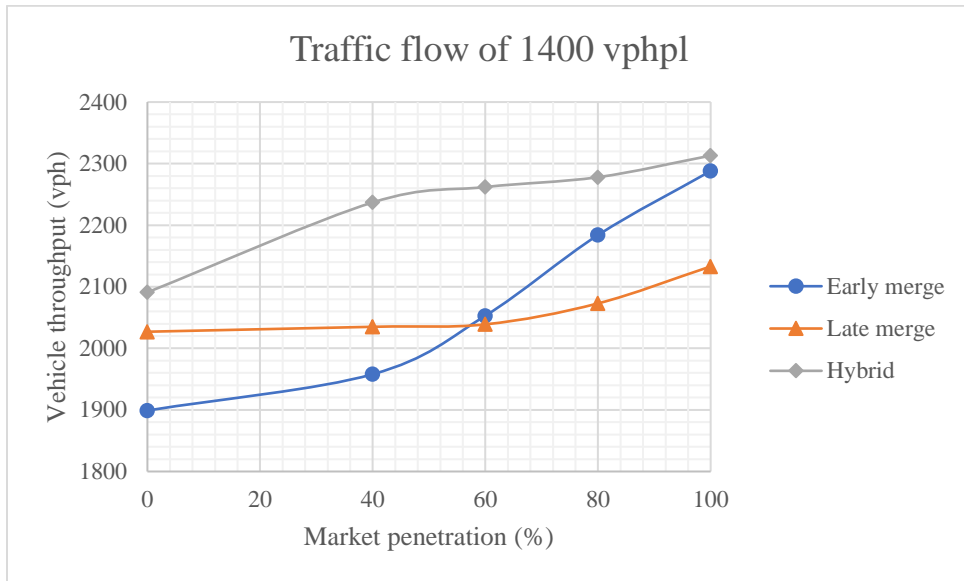


Figure 17: Relationship between vehicle throughput and market penetration at 1,400 vphpl

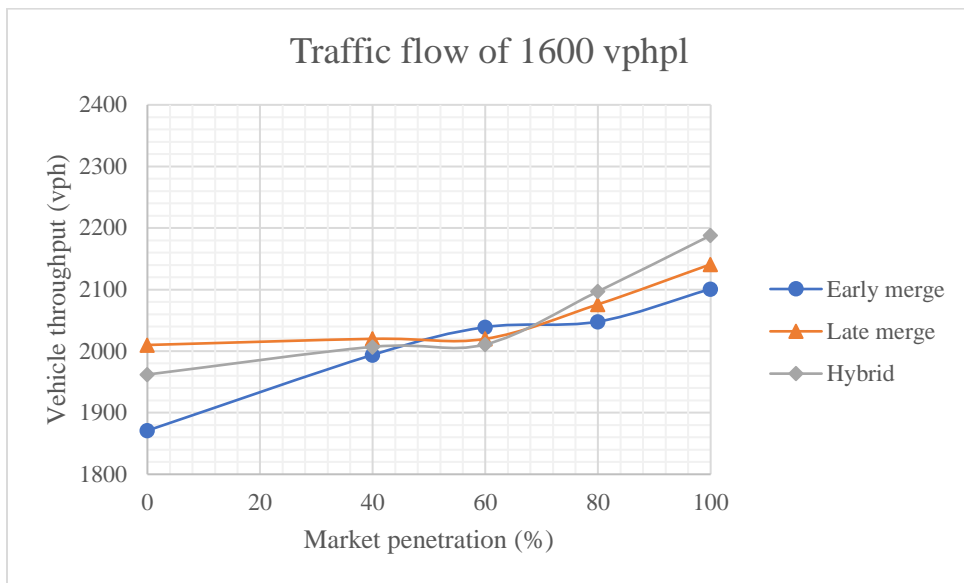


Figure 18: Relationship between vehicle throughput and market penetration at 1,600 vphpl

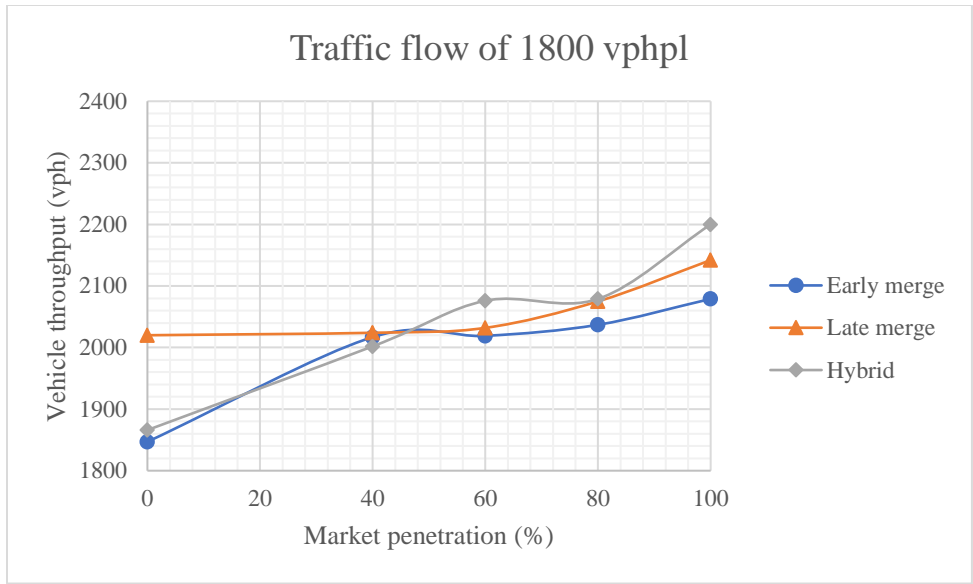


Figure 19: Relationship between vehicle throughput and market penetration at 1,800 vphpl

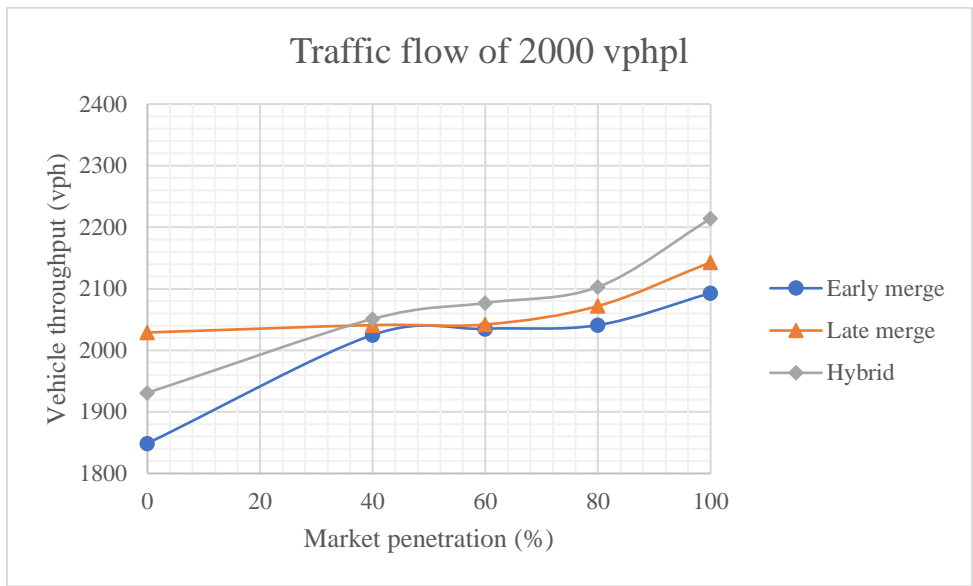


Figure 20: Relationship between vehicle throughput and market penetration at 2,000 vphpl

From the graphs shown, at 1,000 vphpl traffic flow, almost all vehicles could pass through the work zone. The vehicle throughput in this case is quite similar except for the late merge strategy which is a little bit lower at higher market penetration. At 1,200 vphpl traffic flow, vehicle throughput of late merge strategy is significantly higher than the other strategies because both early merge and hybrid could perform much better at low traffic flow while the late merge strategy

performs a constant rate of vehicle throughput around 2,050 vphpl. The vehicle throughput of early merge and hybrid strategies start decreasing when the traffic flow is higher than 1,400 vphpl. From traffic flow of 1,400 vphpl to 2,000 vphpl, they are higher than late merge strategy at the market penetration higher than 40% to 60%. In a big picture, vehicle throughput of hybrid strategy is higher than early merge strategy at most cases. Both vehicle throughput of early merge and hybrid strategies are higher than late merge strategy at low traffic flow, lower than 1,400 vphpl. Meanwhile, at high traffic flow, the vehicle throughput of early merge and hybrid strategies are lower than late merge strategy at low market penetration, from 0% to 40%, but higher than late merge strategy at high market penetration, from 40% to 100%. The vehicle throughput of late merge strategy does not change much with different traffic flow and also with different market penetration from the previous section. It approximately has an average of 2,050 vphpl to 2,065 vphpl.

To conclude, the higher market penetration of level 3 automated vehicle has significant impact to the vehicle throughput of the early merge and hybrid strategies while it has slightly impact to late merge strategy. For both early merge and hybrid strategies, vehicle could change lane at any time after passing through the advance warning sign. Therefore, vehicle could perform the lane change behavior more than late merge strategy which could only merge at the merge point. Moreover, early merge and hybrid strategies could perform better than late merge at low traffic volume or lower than 1,400 vphpl. At high traffic volume or higher than 1,600 vphpl, the early merge strategy has less vehicle throughput than late merge at all market penetration while the hybrid strategy has higher vehicle throughput than late merge at market penetration higher than 60%. Therefore, the hybrid strategy could be the best practice for passing the work zone on 2-to-1 lane drop freeway regarding to the vehicle throughput.

4.2.2 Travel time

4.2.2.1 Travel time and traffic flow at each market penetration

For the second performance measurement, the number of vehicle travel time is compared between each merge scenario regarding to each traffic flow and each market penetration. Figure 21 to figure 25 show the relation between vehicle throughput and traffic flow at each market penetration for all three merging strategies as follows:

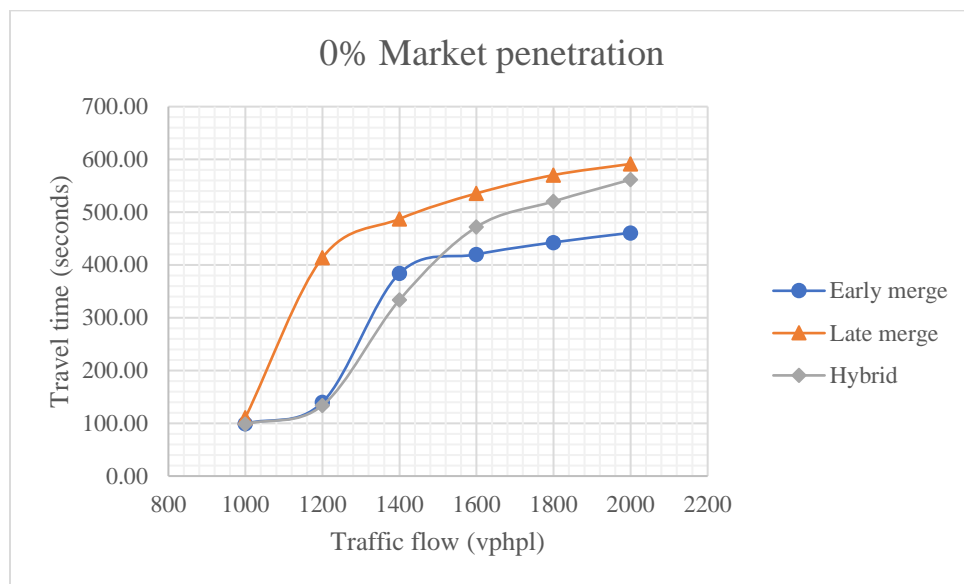


Figure 21: Relation between travel time and traffic flow at 0% market penetration

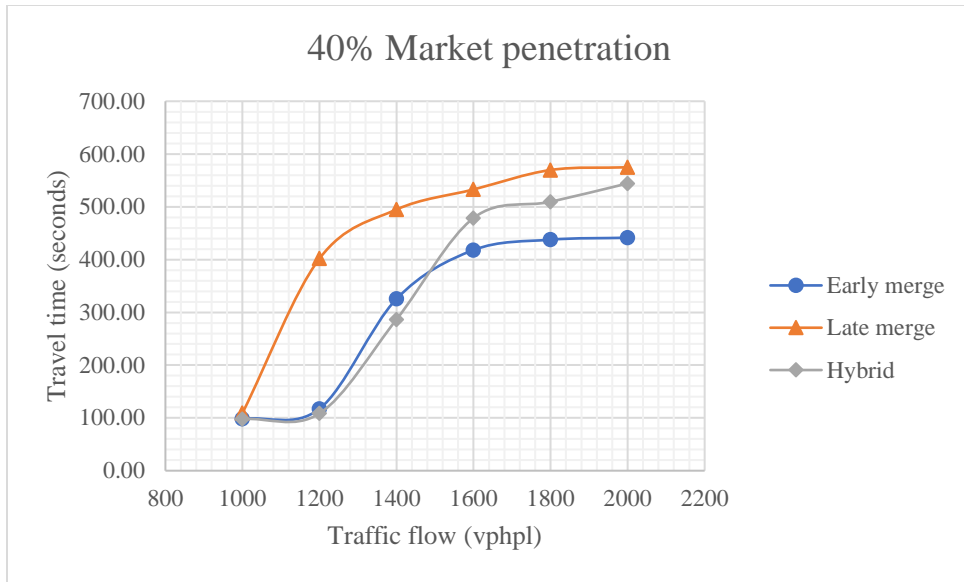


Figure 22: Relation between travel time and traffic flow at 40% market penetration

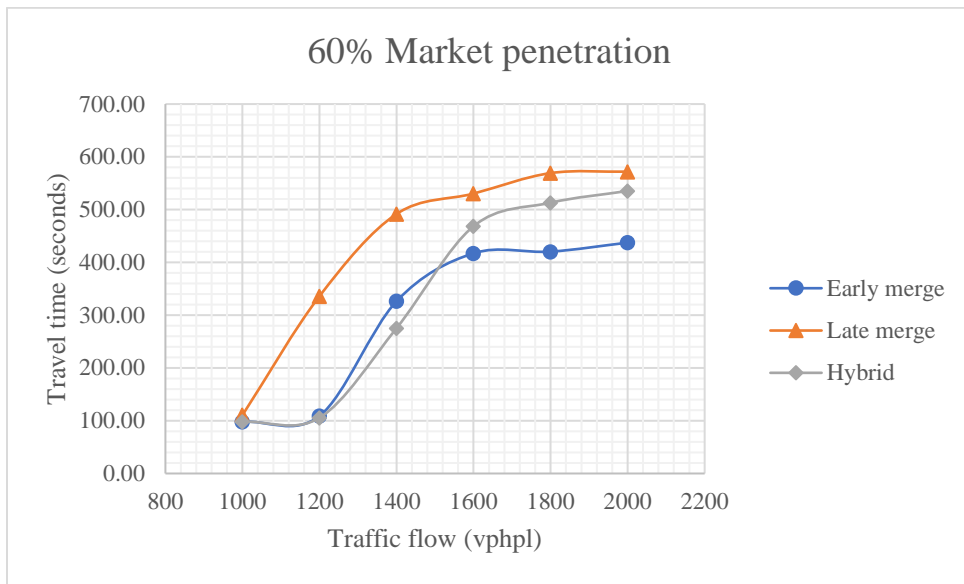


Figure 23: Relation between travel time and traffic flow at 60% market penetration

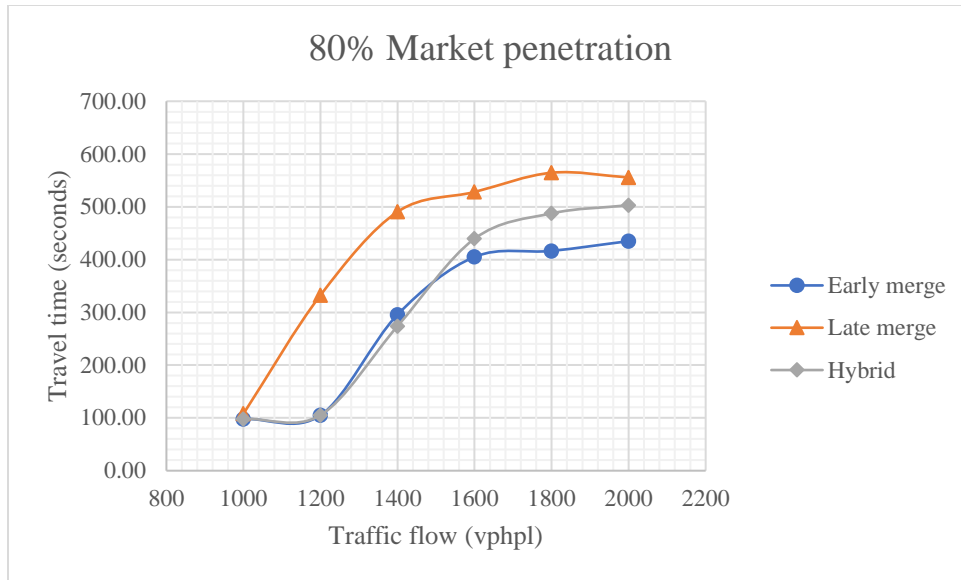


Figure 24: Relation between travel time and traffic flow at 80% market penetration

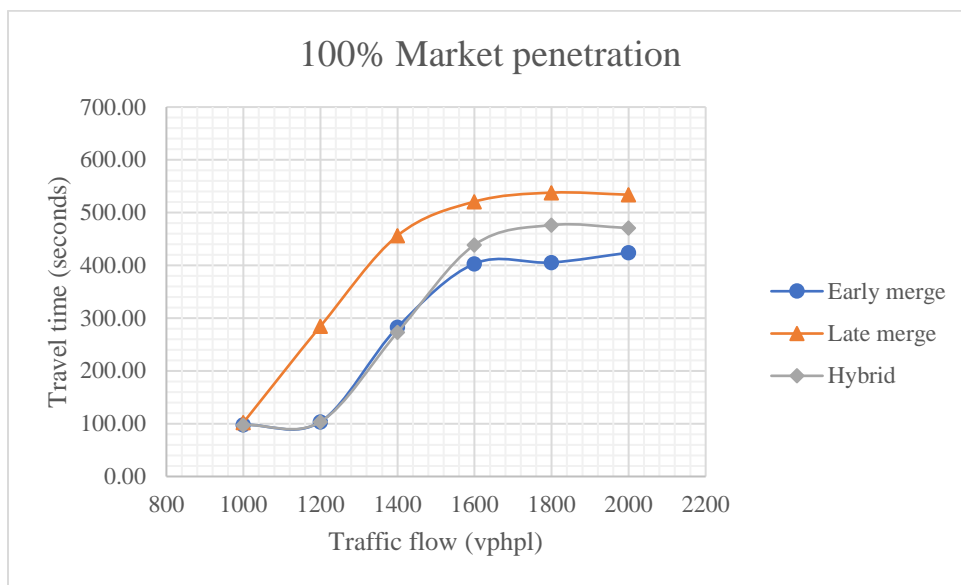


Figure 25: Relation between travel time and traffic flow at 100% market penetration

According to the graphs shown, the travel time trends with the traffic flow from 1,000 vphpl to 2,000 vphpl at every market penetration of level 3 automated vehicle are quite similar. The travel time in late merge strategy is the highest from all strategies because vehicle needs to queue up and have a stop and go movement due to the zipper merge pattern at the merge point. Early merge strategy has minimum travel time than other strategies at the flow higher than

1,400 vphpl. Since the travel time is measured from the advance warning area to the end of the work zone, it does not include the travel time when there is a queue upstream to the advance warning sign. Vehicle tries to merge before it reaches the merge point which could cause traffic jam at upstream traffic. About 1,000 feet before the merge point, only the open lane is used where vehicle does not need to be aware of the lane changing vehicle from another lane and could travel through the work zone faster. It could pass through the area with lower travel time, but the number of vehicle throughput is also lower from the unused capacity of roadway. For the hybrid strategy, it has minimum travel time than other strategies at the flow lower than approximately 1,500 vphpl. At low traffic flow, the hybrid strategy could perform early merge strategy until vehicle reaches the merge point. Therefore, vehicles could continue moving to the merge point if it could not find the acceptable gap to merge and performs zipper merge pattern at merge point. When the zipper merge pattern is performed, the travel time starts to be higher because the stop and go movement has occurred. Thus, the travel of hybrid strategy is higher than early merge strategy, but still lower than late merge strategy, at the traffic flow higher than 1,500 vphpl.

In conclusion, the lowest to highest travel time of merge strategies are early merge, hybrid and late merge respectively. According to the vehicle throughput of early merge strategy, it has the lowest vehicle throughput even it has the best result of travel time. Meanwhile, the vehicle throughput of late merge strategy at high traffic flow is higher than early merge strategy even it has the highest travel time. Therefore, the zipper merge pattern could be useful for high traffic flow with the reason that it allows vehicle to move slowly to merge with less back up traffic as from early merge strategy. However, the hybrid strategy could perform with higher vehicle throughput and less travel time than late merge strategy. Moreover, hybrid strategy has higher travel time than early merge strategy at high traffic flow, but it has significantly higher vehicle

throughput, which is higher than late merge strategy, than early merge strategy. Therefore, hybrid strategy could be the best practice for this study even it does not have the lowest travel time in the temporary traffic control zone.

4.2.2.2 Travel time and market penetration at each traffic flow

Figure 26 to figure 31 show the relation between vehicle throughput and traffic flow at each market penetration for all three merging strategies as follows:

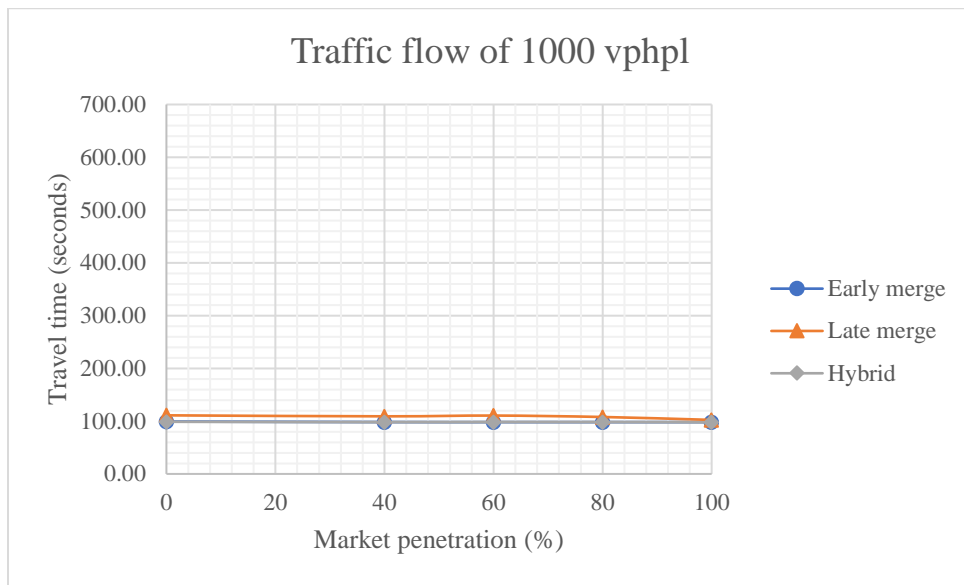


Figure 26: Relationship between travel time and market penetration at 1,000 vphpl

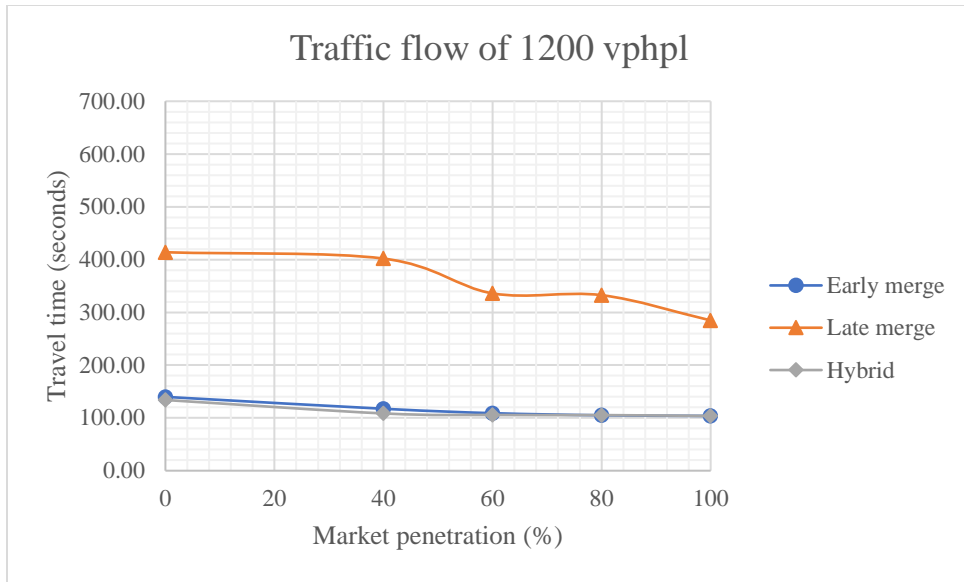


Figure 27: Relationship between travel time and market penetration at 1,200 vphpl

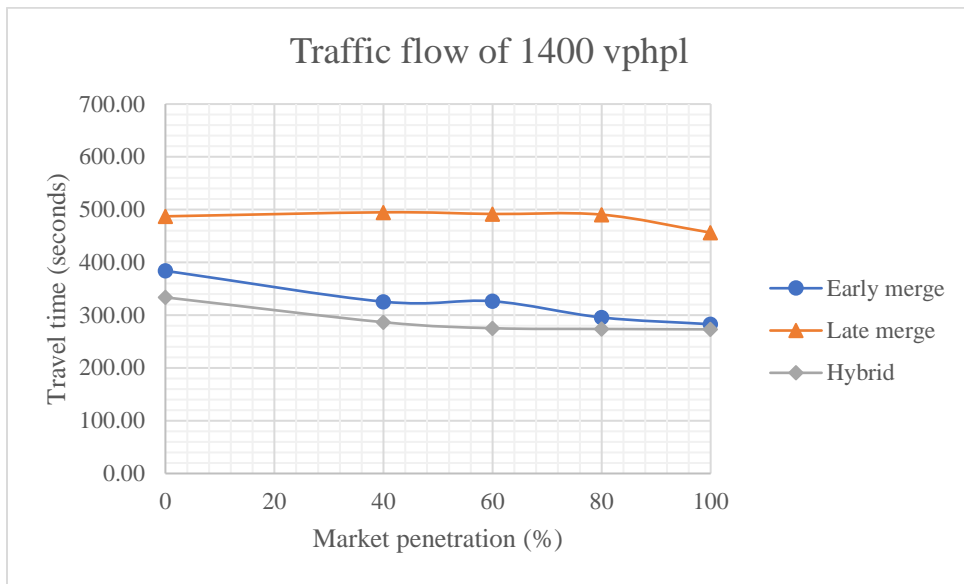


Figure 28: Relationship between travel time and market penetration at 1,400 vphpl

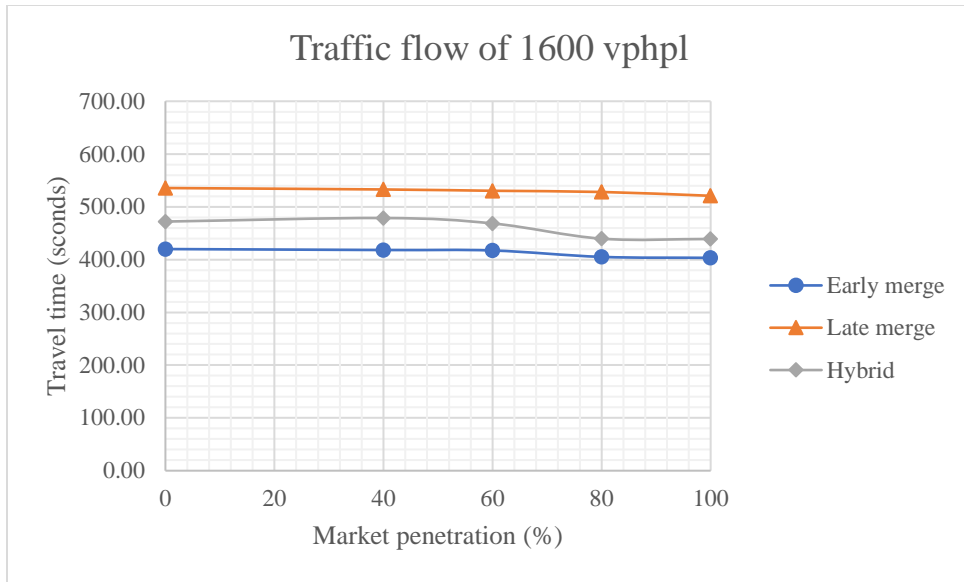


Figure 29: Relationship between travel time and market penetration at 1,600 vphpl

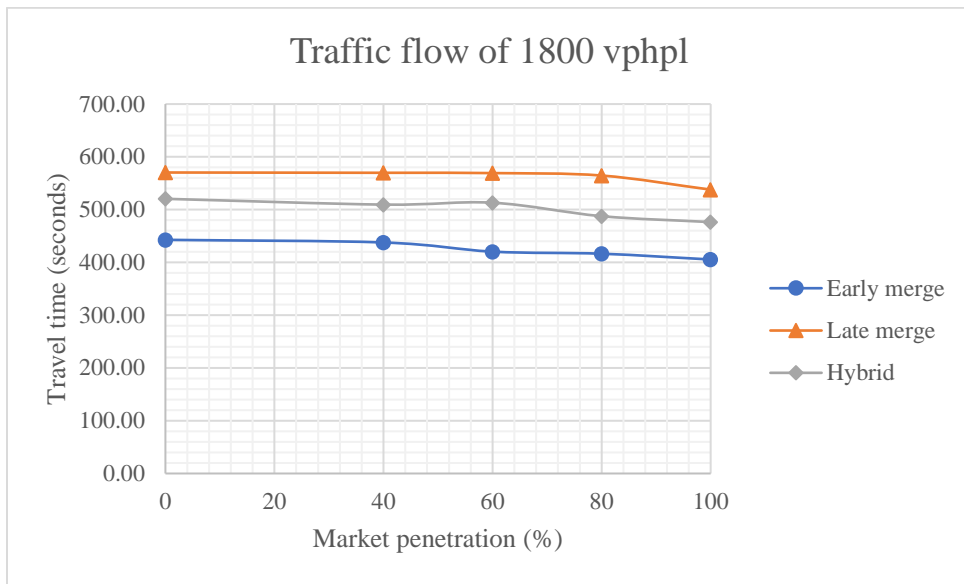


Figure 30: Relationship between travel time and market penetration at 1,800 vphpl

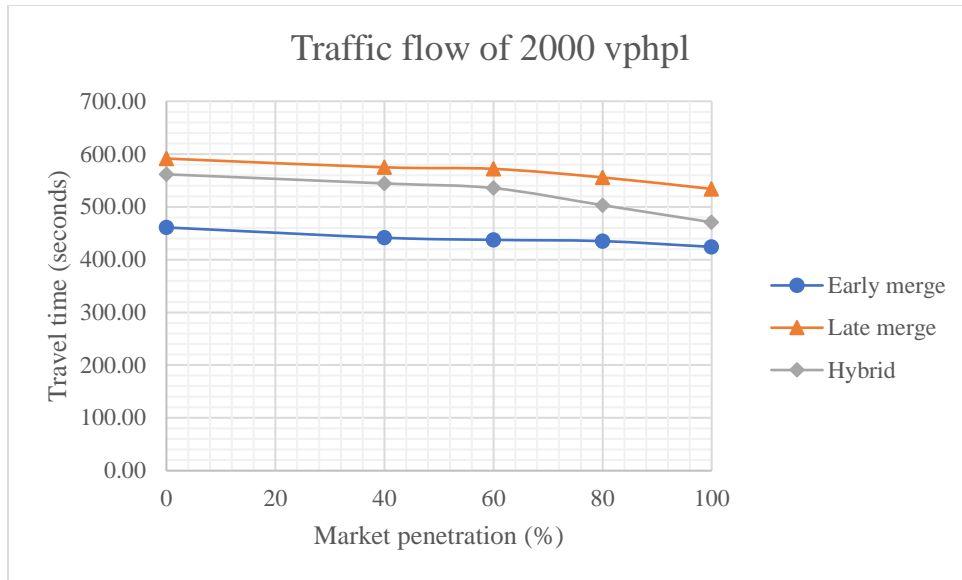


Figure 31: Relationship between travel time and market penetration at 2,000 vphpl

According to the graphs shown, the travel time of all the merging strategies have the same trend which is lower when there is higher market penetration of level 3 automated vehicle. Late merge strategy has the maximum travel in all cases. At traffic flow lower than 1,200 vphpl, both travel time of early merge and hybrid strategies has almost the same travel time. At traffic volume higher than 1,200 vphpl, the travel time of hybrid strategy is higher than early merge strategy because the hybrid strategy starts to perform the zipper merge pattern. To conclude, the higher market penetration of level 3 automated vehicle could reduce the travel time of vehicle passing through the work zone on 2-to-1 lane drop freeway.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The purpose of this study is to investigate the best practice of merging strategy with various market penetration of level 3 automated vehicle at different traffic flow. The merging strategy is compared between early merge, late merge and hybrid. According to the data analysis from previous chapter, the major conclusion are as follows:

- Level 3 automated vehicle could improve mobility performance of vehicle passing through the work zone on 2-to-1 lane drop freeway. The higher market penetration of level 3 automated vehicle could increase vehicle throughput and decrease the travel time.
- Hybrid strategy is the best practice for passing through the work zone on 2-to-1 lane drop freeway because it could perform both early merge and late merge strategies at low and high traffic volume respectively.
- The level 3 automated vehicle has significant impact to the early merge and hybrid strategies. Meanwhile, it has slightly impact to late merge strategy.

5.2 Recommendation

According to this simulation network, the simulation network could perform for more realistic as much as possible by simulating regarding to real exist freeway. There are more factors which could affect the driving behavior such as the curvature of roadway, weather condition or truck percentage. Better detail on simulation network could alleviate the better prediction from the simulation tool. Moreover, better investigation of level 3 automated vehicle behavior could be

obtained. Some of the driving behavior parameters in this study is assumed. Once level 3 autonomous is operated in traffic, the better prediction of traffic control could be done.

5.2.1 Future work

- Dynamic merging

A lot of strategies of temporary traffic control on work zone could be implemented. Although the level 3 automated vehicle in this study is assumed to have low connectivity to be informed from the first advance warning sign, in the future, the automated vehicle could be combined the full connectivity which as known as Connected Automated Vehicle Highway (CAVH). It could have connection feature such as V2V, V2I or V2X communication. Therefore, the dynamic merging strategy could be performed for better performance on merging. VisVAP is recommended to design the simulation in VISSIM.

- Higher level automation

The higher level of automation is expected in the future where human driver could not need to perform anything during the entire trip. The better performance of mobility and safety are expected. Therefore, it would be worth to investigate for the impact which could be different from this study of level 3 automation.

- Other roadway and work zone type

This study only focuses on 2-lane freeway. Work zone could occur any place on roadway in different area. According to the work zone type, it could perform a full closure, partial closure or shoulder closure. The examples of roadway type are urban road, rural road, arterial, etc. Urban road has a lot of factors such as pedestrian and bicycle. The different speed limit on each roadway

type and area could also change the implementation of the temporary traffic control zone. Therefore, there are many of scenarios which could be done and investigated.

- Weather impact

According to the level 3 automated vehicle's ability on perception sensor such as radar. It could detect through the fog, rain and snow which could receive the information from surrounding or monitor the environment better than human driver. To investigate the impact from better performance of perception of automated vehicle could perform more realistic simulation for the study.

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APPENDIX

The example data collected from late merge scenario from VISSIM microsimulation tool is shown in table 9. It shows the vehicle throughput data and vehicle travel time data of 10 simulation runs in a simulation of late merge scenario with 100 market market penetration at 1,800 vphpl as follows.

Table 9: Example data of late merge scenario

Simulation run	Vehicle throughput (veh/hr)	Travel time (sec)
1	2141	537.10
2	2144	547.44
3	2132	538.75
4	2145	546.05
5	2149	544.85
6	2142	522.49
7	2148	536.77
8	2134	533.82
9	2145	542.81
10	2141	528.27